UNIVERSITY OF CALIFORNIA
COLLEGE OF AGRICULTURE
AGRICULTURAL EXPERIMENT STATION
BERKELEY, CALIFORNIA

SOLAR ENERGY AND ITS USE FOR HEATING WATER IN CALIFORNIA

F. A. BROOKS

BULLETIN 602
NOVEMBER, 1936

UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA

CONTENTS

SOLAR ENERGY AND ITS USE FOR HEATING WATER IN CALIFORNIA[1]

F. A. BROOKS[2]

PRACTICALLY ALL THE ENERGY on the earth's surface has sunshine as its primary source. Hydroelectric energy is obtainable because sunshine promotes evaporation of moisture; great masses of air containing this water vapor circulate so that water from low levels is carried back to higher levels, constantly replenishing the lakes and rivers. Wood and agricultural products used for fuel cannot grow without sunshine, and coal and petroleum are the concentrated carbon products of age-old plant and marine life that used the sunshine of past geologic time.

Direct use of solar energy as heat is now being made by several thousand solar water heaters in California. Successful use depends, of course, on the number of sunshine days in different parts of the state. Maps on pages 10 and 11 indicate the general availability of sunshine in California. There are two common types of solar water heaters and several methods of combining the solar heater with other water-heating systems. Recommendations for installations and construction of solar water heaters are to be found on pages 45 and 54.

Investigations and experiments concerning water temperatures and the rate of heating water in different solar-heater systems are described on pages 31 to 43. The results of the experiments are incorporated in the recommendations mentioned above.

The technical nature and availability of solar energy, discussed on pages 4 to 22, may not be of interest to the home owner but must be considered in studying the theory of solar water heaters. The information collected in this first section may be of use also to agricultural scientists concerned with radiation, evaporation, and plant growth.

AVAILABILITY OF SOLAR ENERGY

The quantity of solar energy reaching the earth's surface is so great that there need never be any fear of lack of energy for the earth as a whole. Every square mile of ground in California receives during each clear summer day about as much energy as can be produced by all the power plants of one of the largest electric utility systems in the state.

[1] Received for publication June 22, 1936.

[2] Associate Professor of Agricultural Engineering and Associate Agricultural Engineer in the Experiment Station.

Unfortunately, this vast amount of solar energy is not easily utilized for power; but for heat, part of it is readily available during the daytime in clear weather.

The amount of radiant energy coming from the sun is almost constant—7.15 B.t.u.[3] per square foot per minute—on a surface perpendicular to the sun's rays and outside the earth's atmosphere.[(4)4] Reflection and scattering of the sun's rays by water, dust, and gas molecules decrease the amount of solar energy entering the lower atmosphere. Absorption by water vapor, ozone, and carbon dioxide gases in the atmosphere further diminishes the solar radiation reaching the earth's surface.

NATURE OF SOLAR RADIATION REACHING THE EARTH'S SURFACE

Curve I of figure 1[(22)] shows the energy distribution with respect to wave length in the normal solar spectrum outside the atmosphere, and curves II to V inclusive show the energy distribution after average depletion due to scattering by the dust and gases of the atmosphere. Curve VI indicates the response curve of the eye, yellow light being the most visible. Curve VII shows the diffuse energy received from the sky from the scattering of the direct rays by water, dust, and gas molecules. Without this scattering the sky would be dark, and the stars visible in the daytime. In general, more than one-sixth of the total energy reaching sea level is this diffuse radiation of predominantly short-wave length. On a horizontal surface at sea level the diffuse radiation is relatively constant throughout the greater part of the daytime, ranging from about 0.4 to 0.6 B.t.u. per square foot per minute.

Observations by Coblentz and Kahler[(10)] near Washington, D. C., show that the total solar energy received at sea level may vary even on clear days more than 25 per cent (from 3.64 to 4.86 B.t.u. per square foot per minute) at noontime in September. Of this the ultraviolet part (300 to 389 mμ)[5] of the radiation ranges from 1 to 2 per cent of the total energy. The visible component (389 to 750 mμ), averaging about 47 per cent of the total energy, ranges from 40 to 52 per cent, while the infrared (750 to 3,000 mμ) averages about 52 per cent and ranges from 59 to 46 per cent of the total energy.

Atmospheric Depletion of Solar Energy.—The large variation in energy received on the earth's surface on clear days at the same time of

[3] B.t.u. or British thermal unit = quantity of heat required to raise the temperature of 1 pound of water 1 degree F.

[4] Superscript numbers in parentheses refer to "Literature Cited" at the end of this bulletin.

[5] mμ or millimicron = 1×10^{-9} meter.

year indicates great differences in the composition of the atmosphere and in the quantity of suspended particles of smoke or dust. The absorptive effect of heavy smoke over large industrial cities can be judged by the simultaneous observations[24] showing that the intensity of sunshine in Chicago may be only 55 per cent of that at Madison, Wisconsin. This turbidity indicates approximately a half ton of soot in the air per square mile.

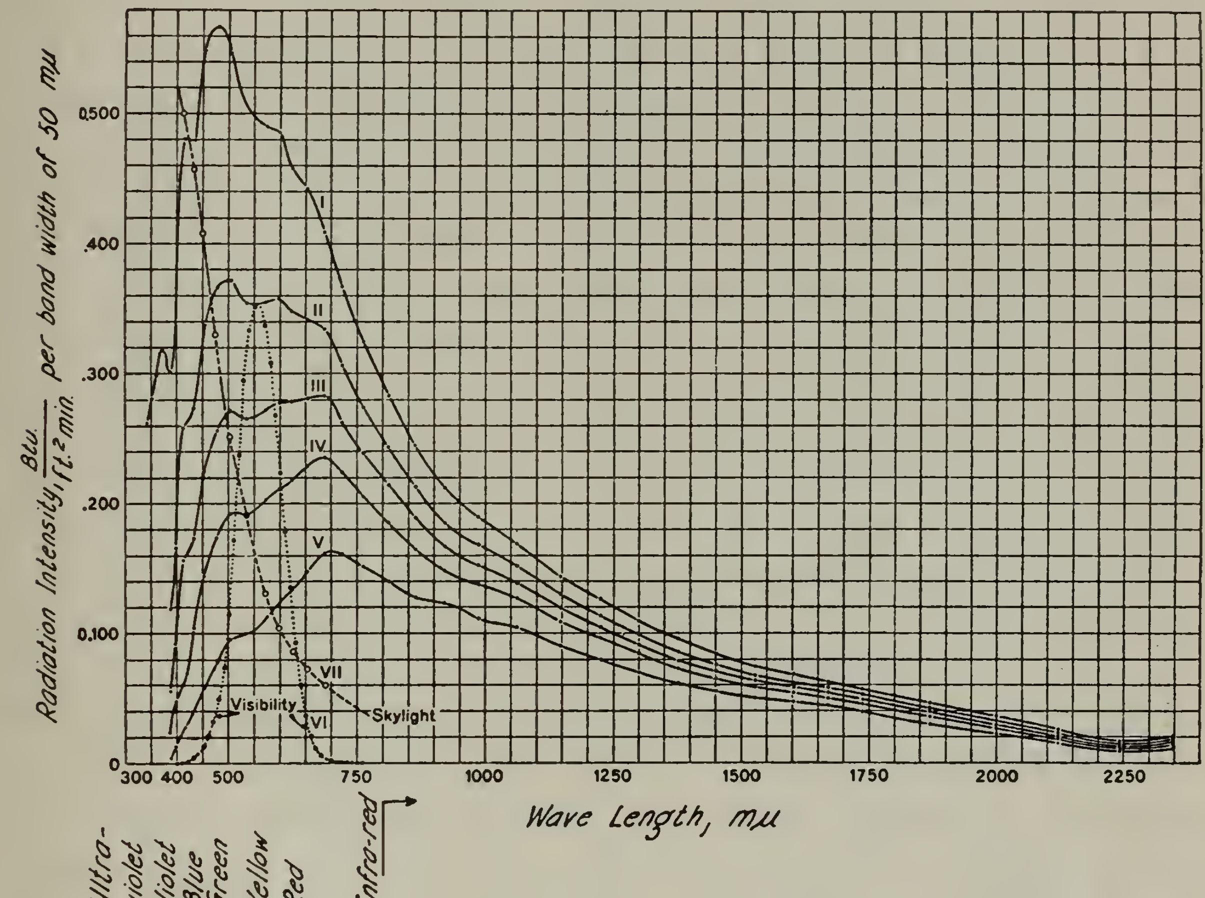

Fig. 1.—Solar radiant energy distribution:
I, Normal solar-energy curve outside the atmosphere.
II, Solar-energy curve; solar altitude at 65°.
III, Solar-energy curve; solar altitude at 30°.
IV, Solar-energy curve; solar altitude at 19.3°.
V, Solar-energy curve; solar altitude at 11.3°.
VI, Relative visibility of radiation.
VII, Skylight-energy curve, Mount Wilson, California.

Except during great dust storms, the depletion due to dust in the atmosphere is less obvious than that due to smoke. The usual fine atmospheric dust, when considered as including smoke, haze, and liquid particles, can be estimated as causing about 10 per cent depletion[24] at midday and, of course, more as the sun approaches the horizon when the sun's rays pass more obliquely through air for a greater distance. The dense dust cloud that passed over Washington, D. C., on May 11, 1934, was over a mile thick and contained about 100 tons[17] of dust per square

mile, reducing the solar radiation received to one-fourth its usual value. In Wisconsin on May 10, when the dust storm covered a large section of the Middle West, one could see the sun shining faintly, and the brightness was less than 1 per cent[14] of its normal value.

Direct Solar Radiation Intensities at Fresno.—Variation in atmospheric depletion caused by the difference in length of path of the sun's rays through the air at different times of day can be judged by the observations in table 1, made at Fresno, California,[26] and from curves II, III, IV, and V of figure 1. In December the more sloping rays of the winter sun have a longer air path, but at the same time the earth is nearer the sun and the solar radiation is nearly 7 per cent more intense. The winter atmosphere, furthermore, is more clear in the interior valleys of California than the summer. These two effects serve to minimize the difference between summer and winter total radiation intensities, and at noon on clear winter days the energy received on a perpendicular surface is approximately 80 per cent of the yearly maximum. The observations recorded in table 1 show that the March intensity in California is 9 per cent higher than the corresponding October figure because of different atmospheric conditions in the spring and fall. These are direct radiation observations and if increased for diffuse sky radiation, according to the Mt. Whitney ratio, indicate that the total energy received on a perpendicular surface at noon is approximately 5.5 and 6.0 B.t.u. per sq. ft. min. in October and March respectively. Comparable July and December figures of 5.4 and 4.8 can be deduced from the noon maximums in figure 2. Hence, for practical purposes, except in the winter time, the total perpendicular noon radiation can be taken as about 5.5 B.t.u. per sq. ft. min. A safe assumption for the 6 or 8-hour daily heating period is 5 B.t.u. per sq. ft. min. total solar energy impinging on a surface perpendicular to the sun's rays.

The insolation at right angles to the sun's rays is of interest in plant transpiration and photosynthesis, but for soil heating and water-surface evaporation the energy received on a horizontal surface is more important. The essential difference is that the reception area of a horizontal surface is less than that of a normal surface in proportion to the cosine of the angle of incidence (or the sine of the sun's altitude above the horizon).

Solar Energy Received on a Horizontal Surface at the Ground.—The regular Weather Bureau pyrheliometers measure the insolation on a horizontal surface inside a spherical glass. The readings, being based on a calibration with an uncovered master pyrheliometer, represent the energy received outside the instrument. Figure 2 shows the average

TABLE 1

DIRECT SOLAR RADIATION INTENSITIES AT FRESNO, CALIFORNIA
(B.t.u. per square foot per minute on a surface perpendicular to the sun's rays)

Season	Sun's altitude above the horizon									
	90°*	54°* Noon	41.8° (10:10 a.m., 1:20 p.m.)	30° (8:45 a.m., 2:45 p.m.)	23.6° (8:05 a.m., 3:25 p.m.)	19.5° (7:45 a.m., 3:50 p. m.)	16.6° (7:30 a.m., 4:05 p.m.)	14.5° (7:20 a.m., 4:15 p.m.,	12.8° (7:10 a.m., 4:25 p.m.)	11.5° (7:05 a.m., 4:30 p.m.)
Oct. 7, 1928, a.m.	....	....	4.50	4.05	3.47	2.99	....	....	....	....
Oct. 8, 1928, a.m.	....	....	4.61	4.09	3.83	3.39	....	....	....	....
Oct. 10, 1928, a.m.	....	....	....	....	3.87	....	....	....	....	....
Means	*5.12*	*4.91*	4.56	4.07	3.72	3.19	....	....	....	....
Average ratio, Oct. a.m.	....	*100%*	93%	83%	76%	65%	....	....	....	....
Oct. 6, 1928, p.m.	*5.01*	....	4.65	4.27	3.94	3.65	3.39	3.13	....	2.65
Oct. 7, 1928, p.m.	*5.12*	....	4.72	4.31	4.05	3.80	....	....	....	....
Oct. 8, 1928, p.m.	*5.23*	....	4.71	4.42	4.16	3.72	....	....	....	....
Means	*5.12*	*4.91*	4.72	4.33	4.05	3.72	3.39	3.13	....	2.65
Average ratio, Oct. p.m.	....	*100%*	96%	88%	82%	76%	69%	64%	....	54%
March 14, 1920, a.m.	*5.60*	....	5.23	4.94	4.64	4.35	4.09	3.87	3.61	3.35
March 14, 1920, p.m.	....	....	5.23	4.90	4.57	4.24	3.95	3.69	3.43	3.21
Means	*5.60*	*5.42*	5.23	4.92	4.61	4.29	4.02	3.78	3.52	3.28
Average ratio, March	....	*100%*	96%	91%	85%	79%	74%	70%	65%	60%
Average ratio, March and Oct. p.m.	....	*100%*	96%	90%	84%	78%	72%	67%	....	57%

* Extrapolated.

daily record for clear weather at Fresno in July and December, 1933. The relation of the horizontal receiving surface to a normal surface is, of course, zero at sunset and sunrise. It is 0.97 at noon in July and 0.50 at noon in December. The most important seasonal variation is the

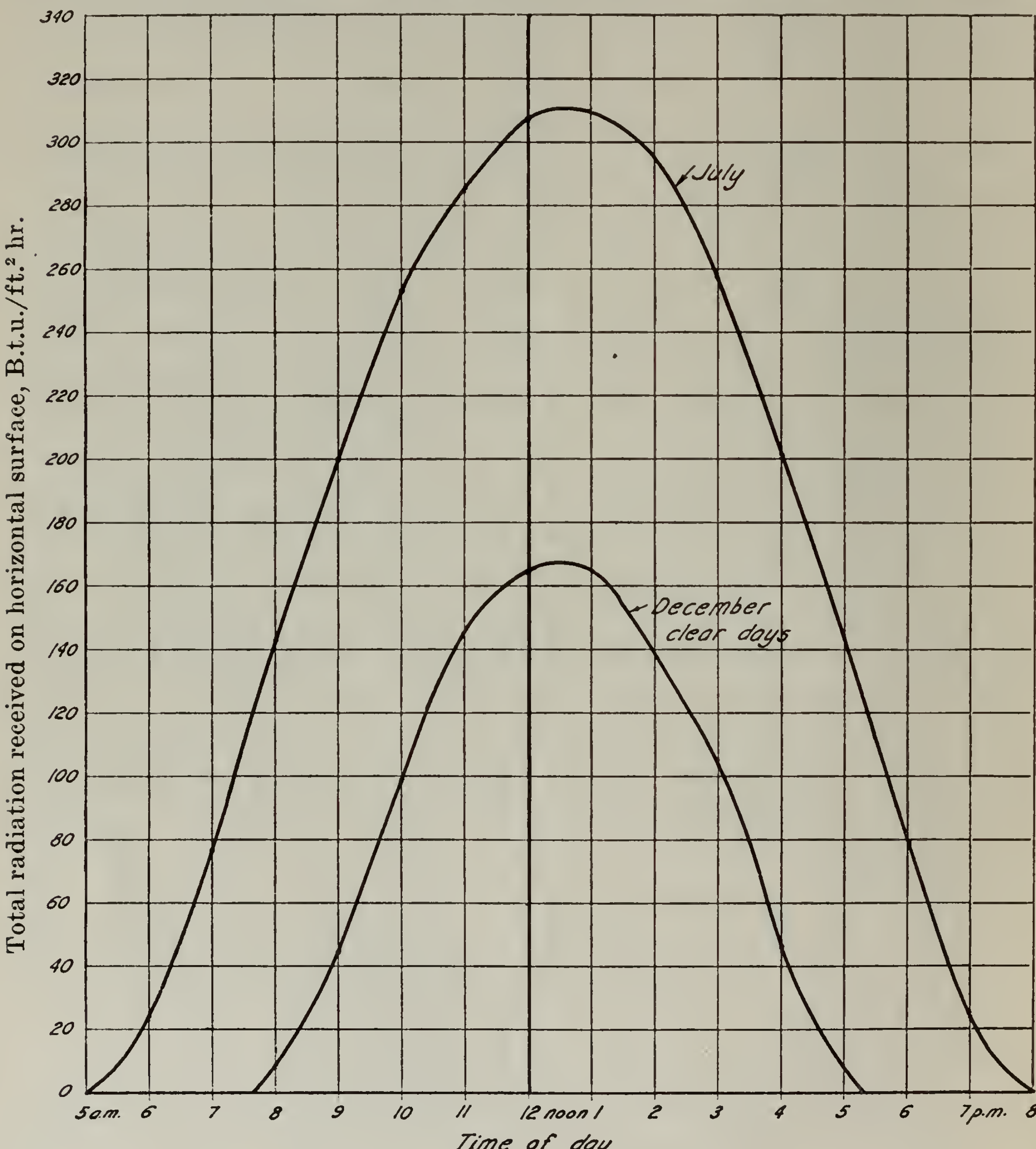

Fig. 2.—Average hourly solar radiation (direct plus diffuse) received on a horizontal surface at Fresno in July and on clear days in December, 1933.

number of hours of sunshine—nearly 15 in midsummer, but only a little more than 9 in midwinter.

The area under the curves represents the total energy received per day. This is the value plotted as the ordinate of figure 3. Any cloudiness would greatly reduce the total daily energy received, as is seen in the published records[35] giving the average daily totals per week. Figure 3 shows the normal annual curves for Fresno, Riverside, and La Jolla. As

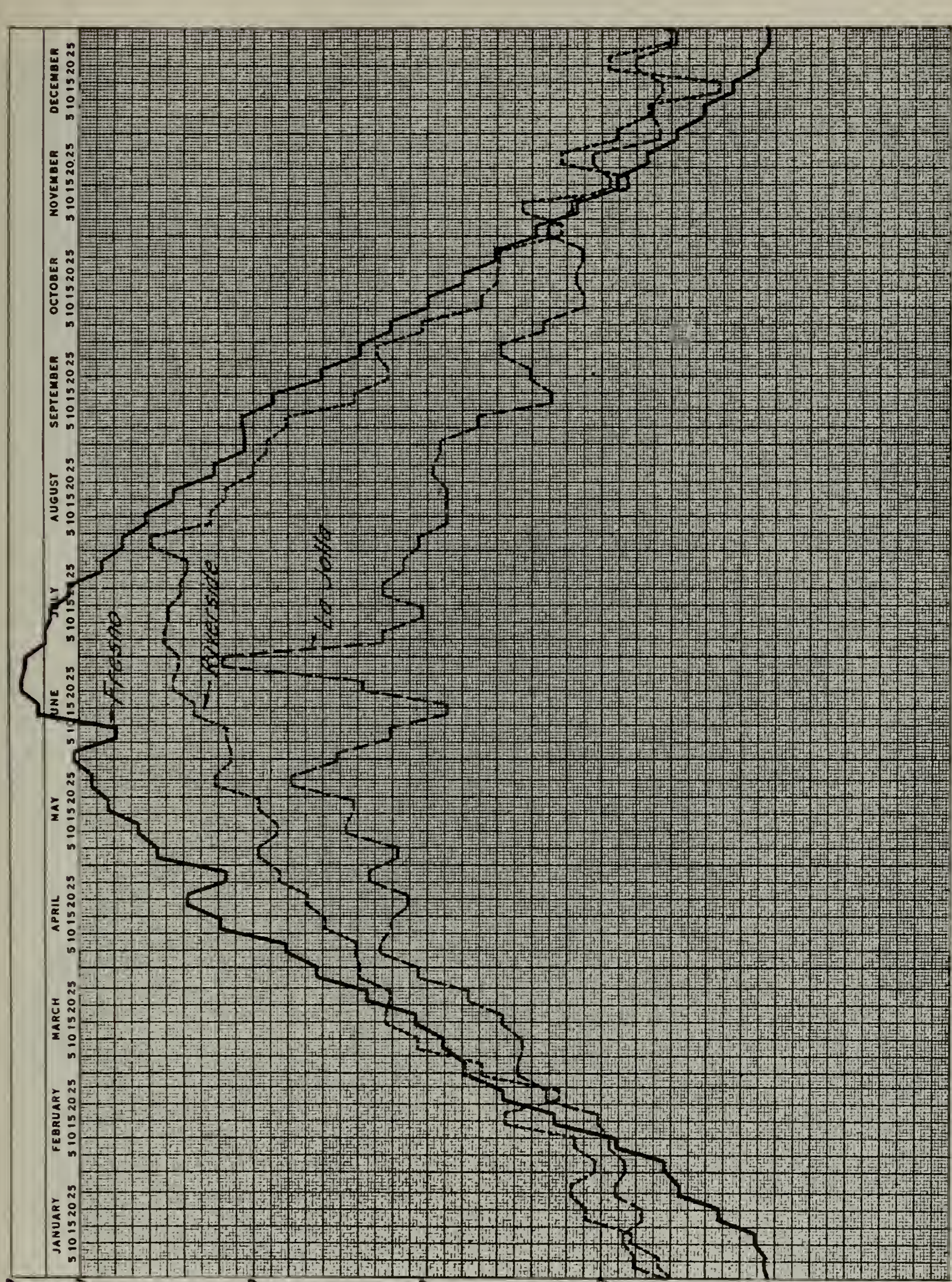

Fig. 3.—Normal daily total solar radiation received horizontally at Fresno, Riverside, and La Jolla.

Fig. 4.—Approximate number of clear days plus half the number of partly cloudy days per year. The unshaded area has the equivalent of about nine months of sunshine days or more per year. (Based on relief map copyrighted by H. A. Sedelmeyer.)

Fig. 5.—Approximate average number of clear days plus half the number of partly cloudy days between latest and earliest frosts. The unshaded area has the equivalent of about seven months or more of sunshine days during the normal growing season. (Based on map coyprighted by H. A. Sedelmeyer.)

the Fresno curve is an eight-year average, its smoothness hides large annual departures (20 to 30 per cent reductions to be expected, especially in the spring) when the usual cloudiness may come in one week or another. The Riverside record is for only two years, and the five-year La Jolla record is not consecutive. As shown in figure 3, although Fresno receives more sunshine for eight months, Riverside and La Jolla both enjoy much more winter sun. The Fresno winter minimum total energy actually received is only 1/6 the summer maximum, although the clear-day record of figure 2 shows the winter energy 37 per cent of the summer. These figures indicate that average winter cloudiness deprives Fresno of more than half the energy that would be available in December to a locality free from clouds.

NUMBER OF DAYS OF SUNSHINE IN DIFFERENT PARTS OF CALIFORNIA

The *Monthly Weather Review*[34] reports the number of clear, partly cloudy, and cloudy days for nearly 200 California localities. As only nine stations report the percentage of possible sunshine, for a general understanding one must use the cloudiness reports. The number of clear days at any one station does not represent fairly the total available sunshine because of a possible large number of partly cloudy days. By definition[6] "partly cloudy" indicates sunshine, on the average, for about half the day. In estimating, therefore, the total number of days of available sunshine, one may reasonably include half the number of "partly cloudy" days with the number of "clear" days. This arbitrary interpretation of the reports of the past ten years shows a consistent distribution of available sunshine throughout the state. As figure 4 shows, almost all the major agricultural areas of the state have the equivalent of nine months of sunshine or more per year. Large variations occur annually, and there are pronounced local differences. Table 2, giving the ten-year figures for a large selected group of stations, shows the general effect of topography and water on the weather. More variation is seen in figure 4 from 204 sunshine days per year at Santa Ana to 310 at Corona, 20 miles away across the Santa Ana mountains; and from 215 days at San Francisco to 302 days at Alvarado, only 23 miles away across the San Francisco Bay.

Nearly 300 sunshine days or more per year are reported at many other stations besides Corona and Alvarado, namely, Barrett Dam, Blythe, Fairmont, Fontana, Greenland Ranch, Helm, Hollister, Imperial, Lancha Plana, Napa, Oakdale, Ojai, Santa Barbara, Trona, Watsonville,

[6] Clear = sun obscured for 0 to 0.3 of the day; partly cloudy = obscured for 0.4 to 0.7 of the day; cloudy = obscured for 0.8 to the whole day.

and Yorba Linda. As this list shows, large areas of California enjoy the equivalent of ten months of sunshine annually.

Ten-Year Records of Average Sunshine, Frost Dates, and Seasonal Temperatures.—Winter sunshine is not, however, so effective as summer radiation; and the ordinary solar water heater may freeze in cold weather. The cloudy days occur, furthermore, mostly in the cold months of November, December, January, and February, so that the sunshine record of figure 5, taken for the normal growing season from average latest spring frost to average earliest fall frost, shows the number of days of most effective insolation. It is to be noted again that the major agricultural areas have the equivalent of seven months or more of sunshine between frosts. The relation between total days and sunshine days between frosts can be found by comparing columns *12* and *13,* table 2. Frost dates observed at stations on tops of city buildings are not comparable with observations at ground level in open country. Maps of frost dates and growing seasons are given in the United States Department of Agriculture *Climatological Data.*[36]

The average temperature data, by seasons (table 2, columns *14, 15, 16,* and *17*) are useful in estimating the relative rates of heat loss of sunshine-absorbing surfaces exposed to the air. The seasonal vapor pressures[13] of a few stations (columns *18, 19, 20,* and *21*) are of interest, for water vapor is largely responsible for the decrease in solar radiation penetrating the atmosphere. The relative humidities (columns *22, 23, 24,* and *25*) are included because of their importance in air-conditioning. The values reported at 5 a.m. and 5 p.m. happen to represent approximately the maximum and minimum relative humidities respectively.

ABSORPTION OF SOLAR ENERGY

Surfaces exposed to the sunlight reflect, transmit, or absorb the incident short-wave solar radiation (fig. 1 and table 1). Exposed surfaces also emit long-wave radiation to the sky or to surrounding surfaces. The absorption and emission of radiant energy depends upon the surface characteristics of the material, the relation of the radiating surface to its surroundings, and the temperatures of the sending and receiving surfaces. The temperature of the sun's surface (more than 11,000° F[4]) is so great that ordinary temperature changes of receiving surfaces on the earth do not affect the incoming radiation rate. Although reradiation from the earth to the sky varies considerably with the temperature, at night with a clear sky it can be assumed to be approximately 0.5 B.t.u. per minute per square foot for a black body.

TABLE 2

TEN-YEAR RECORDS OF AVERAGE SUNSHINE, FROST DATES, AND SEASONAL TEMPERATURES AT SELECTED STATIONS IN CALIFORNIA

Station	Average number of clear and partly cloudy days (upper figure, clear; lower, partly cloudy)				Average number of sunshine* days					Average number of sunshine days between frosts				Average maximum and minimum daily temperatures, degrees F (upper figure, maximum; lower, minimum)				Average vapor pressure, inches of H_2O (upper figure, 5 a.m.; lower figure, 5 p.m.)				Average relative humidity, per cent (upper figure, 5 a.m.; lower figure, 5 p.m.)			
	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.	Year	Average date of latest spring frost	Average date of earliest fall frost	Av. number of days between frosts	Av. number of sunshine days between frosts	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*
Central Valleys																									
Yreka	28	47	70	52	40	58	76	61	235	May 20	Oct. 3	136	110	46	66	85	70	...	...	...	...	...	...	...	...
	25	21	12	17										25	36	51	37	...	...	...	...	...	...	...	...
Fort Bidwell	28	28	52	42	35	40	63	51	189	May 18	Sept. 25	130	89	39	61	85	63	...	...	...	...	...	...	...	...
	14	24	21	17										21	35	50	35	...	...	...	...	...	...	...	...
Red Bluff	31	46	79	60	42	58	84	68	252	Feb. 18	Dec. 6	291	218	56	74	96	77	0.231	0.268	0.326	0.275	86	74	54	67
	21	25	9	18										39	50	64	51	0.250	0.265	0.292	0.278	66	41	21	39
Colusa	44	70	87	73	45	70	87	74	276	Feb. 21	Nov. 25	277	232	56	75	95	77	...	...	...	...	...	...	...	...
	2	1	0	2										37	47	58	48	...	...	...	...	...	...	...	...
Auburn	43	57	82	68	48	62	84	72	266	Mar. 10	Dec. 2	267	213	56	71	91	76	...	...	...	...	...	...	...	...
	10	9	5	7										36	47	61	51	...	...	...	...	...	...	...	...
SACRAMENTO†	34	60	85	69	46	72	88	76	282	Jan. 27	Dec. 10	317	271	54	72	89	75	0.254	0.298	0.367	0.308	89	83	79	78
	23	25	6	14										40	49	57	50	0.279	0.315	0.408	0.335	71	51	38	47
Stockton	30	66	84	69	36	71	87	73	267	Feb. 16	Nov. 27	284	235	56	74	90	76	...	...	...	...	...	...	...	...
	12	9	5	9										37	46	57	50	...	...	...	...	...	...	...	...
Merced	33	65	86	71	41	71	88	76	276	Mar. 1	Nov. 21	265	228	56	75	93	78	...	...	...	...	...	...	...	...
	16	13	4	10										37	47	60	47	...	...	...	...	...	...	...	...
FRESNO	33	53	82	69	46	66	85	75	272	Feb. 9	Dec. 3	297	240	57	76	96	79	0.243	0.279	0.305	0.287	90	80	54	72
	25	27	7	13										40	50	64	52	0.267	0.264	0.246	0.275	65	37	16	36

Porterville.......	40	61	83	68	46	67	85	73	271	Mar. 11	Nov. 24	258	214	59	78	98	81	.....	.....	.....	.....	...	...	...	...
	12	13	4	9										37	47	60	47	.....	.....	.....	.....	...	...	...	...
Bakersfield.......	26	47	75	54	43	64	83	68	258	Feb. 18	Nov. 30	285	220	60	78	99	81	.....	.....	.....	.....	...	...	...	...
	35	34	16	29										37	50	65	50	.....	.....	.....	.....	...	...	...	...
COAST RANGE																									
EUREKA..........	22	21	23	24	31	35	41	36	143	Feb. 14	Dec. 6	295	119	55	57	60	59	0.264	0.281	0.355	0.331	88	89	93	92
	19	29	36	24										42	46	52	48	0.297	0.303	0.371	0.365	80	78	91	82
Weaverville......	35	51	79	63	43	58	83	69	253	May 23	Sept. 17	117	101	50	69	92	75	.....	.....	.....	.....	...	...	...	...
	17	13	8	12										29	35	45	32	.....	.....	.....	.....	...	...	...	...
Santa Rosa.......	38	51	73	64	47	61	81	71	260	Apr. 6	Nov. 9	217	176	59	71	82	76	.....	.....	.....	.....	...	...	...	...
	18	20	15	12										36	42	48	43	.....	.....	.....	.....	...	...	...	...
SAN FRANCISCO...	31	36	41	43	45	53	59	58	215	Jan. 12	Dec. 14	336	201	57	65	67	68	0.285	0.307	0.367	0.362	85	85	91	86
	27	34	36	30										46	51	53	54	0.296	0.313	0.378	0.360	72	70	76	70
Oakland.........	45	50	60	61	54	61	71	69	255	Jan. 27	Dec. 10	317	227	55	63	70	67	.....	.....	.....	.....	...	...	...	...
	18	22	20	17										45	50	55	53	.....	.....	.....	.....	...	...	...	...
San Jose.........	31	40	74	52	44	55	81	65	245	Feb. 11	Dec. 9	301	215	59	70	80	73	.....	.....	.....	.....	...	...	...	...
	25	30	15	26										40	46	53	48	0.298	0.341	0.423	0.357	68	58	53	55
Hollister.........	53	63	88	75	58	70	89	78	295	Feb. 26	Nov. 25	272	249	60	72	82	76	.....	.....	.....	.....	...	...	...	...
	10	12	2	6										38	45	52	46	.....	.....	.....	.....	...	...	...	...
Del Monte.......	46	44	51	52	56	57	64	62	239	Mar. 1	Nov. 18	262	174	58	65	69	67	.....	.....	.....	.....	...	...	...	...
	19	26	26	20										37	44	51	45	.....	.....	.....	.....	...	...	...	...
King City........	47	53	60	69	53	63	72	74	262	Apr. 12	Nov. 2	204	158	63	78	86	81	.....	.....	.....	.....	...	...	...	...
	13	21	23	11										34	42	50	39	.....	.....	.....	.....	...	...	...	...
San Luis Obispo	55	61	76	70	62	68	82	75	287	Feb. 24	Dec. 10	289	231	64	70	77	75	0.243	0.284	0.349	0.308	77	82	86	79
	15	14	11	11										43	47	52	49	0.286	0.328	0.393	0.351	60	64	57	58

* "Sunshine" days = number of clear days plus half the number of partly cloudy days.

† Stations printed in small capital letters are operated by the U. S. Weather Bureau.

(*Table continued on p. 16.*)

TABLE 2—*Concluded*

Station	Average number of clear and partly cloudy days (upper figure, clear; lower, partly cloudy)				Average number of sunshine* days					Average number of sunshine days between frosts				Average maximum and minimum daily temperatures, degrees F, (upper figure, maximum; lower, minimum)				Average vapor pressure, inches of H_2O (upper figure, 5 a.m.; lower figure, 5 p.m.)				Average relative humidity, per cent (upper figure, 5 a.m.; lower figure, 5 p.m.)			
	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.	Year	Average date of latest spring frost	Average date of earliest fall frost	Av. number of days between frosts	Av. number of sunshine days between frosts	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.	Dec. Jan. Feb.	Mar. Apr. May	June July Aug.	Sept. Oct. Nov.
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*
										SOUTHERN REGION															
Santa Barbara	63	65	73	68	70	72	80	74	297	Jan. 27	Dec. 18	325	264	67	71	77	76	.....	.....	.....	.....	...	...	...	...
	14	15	14	12										42	48	56	50	.....	.....	.....	.....	...	...	...	...
LOS ANGELES†	50	40	56	55	60	57	71	67	255	....	....	...	...	67	71	79	76	0.235	0.321	0.454	0.344	66	82	88	74
	20	33	30	24										50	54	61	58	0.299	0.345	0.471	0.403	61	62	62	63
Pomona	48	38	38	50	62	59	64	67	252	Mar. 7	Nov. 20	258	178	64	75	88	79	.....	.....	.....	.....	...	...	...	...
	27	43	52	34										37	45	55	46	.....	.....	.....	.....	...	...	...	...
Elsinore	50	51	70	60	61	63	79	71	274	Mar. 16	Nov. 17	246	194	66	78	96	84	.....	.....	.....	.....	...	...	...	...
	21	25	19	21										33	42	56	45	.....	.....	.....	.....	...	...	...	...
SAN DIEGO	39	35	41	45	52	50	59	60	221	....	....	...	...	64	67	72	71	0.263	0.342	0.488	0.393	72	81	86	78
	26	31	37	31										49	54	63	57	0.361	0.372	0.502	0.451	67	69	73	71
San Bernardino	54	56	71	63	64	68	80	73	285	Mar. 8	Nov. 27	264	213	69	77	93	83	.....	.....	.....	.....	...	...	...	...
	20	24	17	20										39	46	57	48	.....	.....	.....	.....	...	...	...	...
Indio	60	64	68	71	68	70	74	76	288	Feb. 8	Nov. 20	285	229	72	88	104	91	.....	.....	.....	.....	...	...	...	...
	15	13	12	10										40	57	77	57	.....	.....	.....	.....	...	...	...	...
Imperial	64	77	73	77	71	82	81	82	316	Jan. 26	Dec. 4	312	274	71	88	104	90	.....	.....	.....	.....	...	...	...	...
	15	11	16	10										39	54	73	56	.....	.....	.....	.....	...	...	...	...
Blythe	66	75	69	75	73	81	78	80	312	Feb. 16	Nov. 25	282	244	70	89	106	91	.....	.....	.....	.....	...	...	...	...
	13	13	18	10										36	52	72	53	.....	.....	.....	.....	...	...	...	...
Needles	54	58	64	66	60	65	69	71	265	Jan. 28	Dec. 4	310	228	65	87	106	88	.....	.....	.....	.....	...	...	...	...
	12	14	11	9										41	56	76	57	.....	.....	.....	.....	...	...	...	...

* "Sunshine" days = number of clear days plus half the number of partly cloudy days.

† Stations printed in small capital letters are operated by the U. S. Weather Bureau.

Solar-Energy Absorptivity of Various Surfaces and Surface Emissivities at Ordinary Temperatures.—The heating effect of sunshine is modified by the reflectivity of the exposed surface and hence the absorptivities given in table 3 show large characteristic differences. Coefficients for clouds, ground surfaces, and fields are usually given in terms of albedo, namely "the ratio of the intensity of the radiation diffusely reflected from the surface of the earth to the intensity of that received by it."[23] Therefore, some of the absorption factors given in table 3 are determined from 1.00 minus the observed albedo. The cooling effect of out-going radiation also depends upon the surface absorption or emission characteristic. The emissivities given in table 3 for a wave length corresponding to the usual outdoor temperature of the emitting surface are, therefore, different from the short-wave absorptivities. Although data on field plants and various soils are, unfortunately, meager, there is sufficient information to establish the approximate heat balance in such phenomena as the cooled air on the leeward side of an alfalfa field in midsummer, when the sunshine, although intense, does not furnish all the heat of vaporization utilized in transpiration.

Observations of fresh and of soiled snow showing that the soiling effect quadruples the solar energy absorbed led in Russia[1] to spreading coal dust over the snow, about 100 pounds per acre. In this way the spring melting is advanced and permits an early growing season.

Table 3 gives the coefficients of various surfaces for short-wave (0.6μ) absorption and for long-wave (9.3μ) outgoing radiation. In general the short-wave absorption varies roughly as the visual darkness of the surface. Long-wave emissivity cannot be judged visually. Common building materials, paints, and roofs (except asbestos and metals) have nearly perfect emitting surfaces for long-wave radiation. Many common materials exhibit wide differences in short-wave absorption and long-wave emission. Finished plaster absorbs only 35 per cent of the impinging solar radiation and yet is 93 per cent effective as a long-wave radiator. Whitewashing further reduces the solar-energy absorption; and is used in Egypt and Arabia for keeping buildings as cool as possible. In other words, white acts out-of-doors as a one-way heat valve because it reflects most of the sunshine and yet at night readily emits ordinary heat waves to the cold sky. However, new galvanized iron, for example, has a solar absorptivity of 0.66 and a long-wave emissivity of 0.23, indicating high daytime heating and relatively low cooling power by radiation. Polished metals, particularly aluminum, act as radiation shields, being excellent reflectors and also poor emitters. Such properties are valuable for minimizing temperature fluctuations.

TABLE 3

SOLAR ENERGY ABSORPTIVITY OF VARIOUS SURFACES AND SURFACE EMISSIVITIES AT ORDINARY TEMPERATURES

Materials	Short-wave absorption	Long-wave emission	References*
Standards			
"*Hohlraum*," *theoretical perfectly black body*	*1.00*	*1.00*	......
Black silk velvet (minimum reflector)	0.99	0.97	*19, 16*
Magnesium oxide (MgO; standard maximum white)	0.025	....	*30*
Deposited silver (optical reflector) fresh, untarnished	0.07	0.01	*16*
Mirror, silver-backed glass	0.12	....	*16*
Mirror, mercury-backed glass	0.20	....	*16*
Meteorological			
Cloud surface	0.22, 0.26	....	*3, 25*
Water	0.90† (vert.)	0.914, 0.965	*23, 33*
Wet surfaces	....	0.985	*33*
Frosted surfaces, 0.004 to 0.008 inch thick	....	0.985	*33*
Snow, fresh, bright, sparkling (maximum reflection)	0.13	0.74	*21, 16*
Snow, soiled	0.54	....	*21*
Ice	....	0.914-0.965	*33*
Earth's surface as a whole, average cloud cover	0.57	....	*3*
Earth's surface as a whole, land and sea, no clouds	0.83	....	*25*
Ground and pavements			
Soil, surface	....	0.38	*15*
Soil, brown, dry	0.68	....	*19*
Soil, brown, wet	0.84	....	*23*
Sand, Maine, yellow, white grains of many kinds	0.75	0.52	*16*
Sand, Florida, very white	0.60	....	*16*
Gravel	....	0.28	*15*
Granite	0.55	0.44	*7, 15*
Sandstone	0.54-0.76	....	*7*
Limestone	0.33-0.50	....	*7*
Granolith pavement	0.83	....	*15*
Concrete	0.65	0.97	*16, 8*
Asphalt pavement, dust-free	0.93	....	*15*
Vegetation			
Grass, dead turf	0.81, 0.82	....	*21*
Grass, dead, wet (after rain, no sun)	0.85	....	*21*
Grass, 80-90 per cent new green	0.77	....	*21*
Grass, 80-90 per cent new (in sunshine after rain)	0.67	0.98	*21, 33*
Grass, fresh, dry	0.67-0.75	....	*23*
Leaves, green	0.75	....	*16*
Leaves, early summer, high water content	0.81†	....	*23*
Leaves, late summer, after dry period	0.71†	....	*23*
Vegetable mold	....	0.64	*15*
Building material, roofing, etc.			
Sawdust	....	0.75	*15*
Wood, planed oak	....	0.90	*15*
Paper, white	0.28	0.95	*15*
Cotton cloth, white handkerchief	0.58	....	*16*
Artificial leather, black	0.90	....	*9*
Rubber	....	0.90-0.95	*32*
Felt, black	0.86	....	*16*
Felt, roofing, bituminous	0.88	....	*16*
Felt, roofing, aluminized	0.38	....	*16*
Asbestos cement board, white	0.59	0.96	*16, 28*

* Numbers in the reference column refer to "Literature Cited" p. 62.

† Includes transmissivity.

TABLE 3—*Continued*

Materials	Short-wave absorption	Long-wave emission	References*
Building material, roofing, etc.—*Continued*			
Asbestos felt (white impregnated covering for corrugated iron roofing)	0.25 (approx.)	0.50 (approx.)	*9*
Roll roofing, green	0.88	0.91–0.97	*15, 31, 8*
Slate, dark-gray	0.89	....	*15*
Gypsum 0.02 inch thick on smooth plate	....	0.90	*32*
Plaster, finished	0.35	0.93	*15*
Bricks, Gault, cream	0.38	....	*15*
Bricks, sand-lime, red	0.72	0.93	*15, 28*
Glass	0.92†	0.90-0.95	*15*
Paints			
Whitewash	0.22-0.25	....	*16, 27*
Enamel, ceramic white	....	0.90	*31*
Porcelain enamel on steel plate, white	0.34-0.40	0.90	*30, 32*
Porcelain enamel on steel plate, green	0.76	....	*16*
Bright aluminum, 2 coats	0.35-0.54	0.28-0.45	*27, 7, 9*
Fine bronze	....	0.51	*15*
Bronze with 2 coats varnish	....	0.88	*15*
White	0.11-0.18	0.95 (approx.)	*2, 7*
Gloss-white	0.35	0.95 (approx.)	*19*
Cream	0.23-0.26	0.92-0.96	*2, 19, 18*
Light-yellow	0.35		
Light-blue	0.39		
Medium-blue	0.64		
Light-green	0.52-0.53		
Dark-green	0.88		
Red	0.87	0.96	*19*
Lampblack	0.98-0.97	0.96	*2, 16*
Lacquer, black shiny	....	0.82	*31*
Graphite	0.78	0.41	*16*
Metals			
Aluminum sputtered (optical reflector) with oxidized film	0.11	....	*20*
Aluminum, Alcoa lighting sheet, specular finish, weatherproof	0.18-0.20	....	....‡
Aluminum foil	....	0.08	*28*
Aluminum foil with coat of linseed oil	....	0.56	*28*
Aluminum, polished	0.26	0.04-0.05	*15*
Aluminum, oxidized	....	0.11	*15*
Aluminum, commercial polished sheet	....	0.20-0.25	*8*
Duralumin	0.53	....	*15*
Brass, polished	....	0.05	*31*
Brass, as rolled	....	0.07	*15*
Brass, dull	....	0.28	*31*
Brass, oxidized	....	0.61	*15*
Chromium	0.49	0.08	*15*
Copper, polished	0.18	0.04	*7, 15*
Copper, rolled, tarnished	0.64	0.64	*7, 15*
Copper, black oxidized	....	0.78	*15*
Galvanized iron, new	0.65	0.23	*16, 28*
Galvanized iron, oxidized	....	0.28	*28*
Galvanized iron, very dirty	0.91	....	*16*
Galvanized iron, white washed	0.22	....	*16*
Iron, pure, polished	0.45	0.06	*15*
Iron, cast, oxidized	....	0.63-0.98	*15*
Iron, rusted	....	0.62-0.69	*15*

* Numbers in the reference column refer to "Literature Cited" p. 62.
† Includes transmissivity.
‡ Letter from Howard M. Flye, of the Aluminum Company of America, Feb. 25, 1936.

TABLE 3—*Concluded*

Materials	Short-wave absorption	Long-wave emission	References*
Metals—*Continued*			
Iron, rolled oxidized	....	0.66	*15*
Steel, sheet insulation	....	0.28	*37*
Steel, as rolled	....	0.65-0.82	*31, 32*
Steel, oxidized	....	0.79	*15*
Lead, oxidized	....	0.28-0.43	*15*
Lead, old roofing	0.79	....	*16*
Magnesium	0.30	0.07	*15*
Tinned steel plate, bright	....	0.05-0.09	*31*
Zinc, pure, polished	0.46	0.02	*15*
Zinc, polished, oxidized	....	0.28	*15*

* Numbers in the reference column refer to "Literature Cited" p. 62.

Glass is opaque to long-wave radiation and therefore as an emitter of ordinary heat waves acts in the same way as a painted surface. Sunshine or short-wave radiation is readily transmitted, only a few per cent being absorbed by the glass itself. In the sunshine, glass acts as a one-way heat valve: the solar radiation enters with little loss, but the covered surface heated by the sunshine emits long-wave radiation which cannot pass out through glass except by conduction after being reconverted to sensible heat in absorption by the glass. Practically, the trapping of solar heat by glass is opposite to the cooling effect of white surfaces, although for a different reason, namely transmission and opaqueness instead of reflection and emission for short and long-wave radiation respectively.

The Effect of Angle of Incidence on the Amount of Light Transmitted by Glass and Absorbed by a Black Surface.—The total solar energy received by fixed glass-covered absorbers such as greenhouses, cold frames, and solar water heaters is considerably less than the total radiation impinging on a surface perpendicular to the direct rays at noon. The difference can be ascribed partly to greater absorption by the glass, but is due mostly to the smaller portion of rays intercepted on a fixed surface and to the increasing reflection from the glass cover and the absorbing surface as the angle of incidence increases.

In table 4, columns *3* to *7* show these effects of angle of incidence; column *9* shows the Fresno average for atmospheric depletion in March and September due to the length of air path at different times of day as deduced from table 1. The diffuse radiation from the sky (fig. 1, curve VII) is not affected by the angle of incidence, but suffers a larger transmission loss in the glass due to the greater opacity of glass to very short wave-length light. This loss varies greatly with different kinds of glass. Assuming a 25 per cent loss, a fixed absorber exposed to 0.8 of the

TABLE 4

THE AMOUNT OF LIGHT AT DIFFERENT ANGLES OF INCIDENCE ABSORBED BY A GLASS-COVERED BLACK SURFACE FIXED PERPENDICULAR TO THE SUN'S RAYS AT NOON IN MARCH AND SEPTEMBER

Angle of incidence, degrees from perpendicular to glass	Time of day, March and September (solar time)	Effective interception area*	Ratio of transmitted light to incident direct noon radiation**	Proportion of direct radiation transmitted through fixed glass cover,*** per cent	Ratio of direct radiation absorbed by black surface to incident direct radiation (7)	Proportion of direct radiation absorbed by black surface under glass,† per cent	Sun's altitude above horizon at Fresno, March, and September, degrees	Ratio of depleted direct radiation to noon maximum (perpendicular surface)	Proportion of depleted direct noon radiation absorbed by glass-covered black surface,‡ degrees	Additional diffuse radiation received by sloped absorber, per cent	Ratio of total radiation absorbed by glass-covered black surface to depleted direct noon radiation¶
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
0	Noon	1.000 00	0.88	88	0.96	85	54	1.00	85	8	0.93
5	11:40 a.m. or 12:20 p.m.	0.996 19	.88	88	.96	84	53	1.00	84	8	.92
10	11:20 a.m. or 12:40 p.m.	0.984 81	.88	87	.96	83	52	0.99	82	8	.90
15	11:00 a.m. or 1:00 p.m.	0.965 92	.88	85	.96	81	51	0.99	80	8	.88
20	10:40 a.m. or 1:20 p.m.	0.939 69	.88	83	.96	79	49	0.99	78	8	.86
25	10:20 a.m. or 1:40 p.m.	0.906 31	.88	79	.95	76	47	0.98	74	8	.82
30	10:00 a.m. or 2:00 p.m.	0.866 03	.87	76	.95	72	44	0.97	70	8	.77
35	9:40 a.m. or 2:20 p.m.	0.819 15	.87	71	.95	67	41	0.96	64	7	.71
40	9:20 a.m. or 2:40 p.m.	0.766 04	.86	66	.94	62	38	0.94	58	7	.65
45	9:00 a.m. or 3:00 p.m.	0.707 11	.85	60	.94	56	35	0.92	52	7	.59
50	8:40 a.m. or 3:20 p.m.	0.642 79	.83	53	.93	50	32	0.90	45	7	.52
55	8:20 a.m. or 3:40 p.m.	0.573 58	.80	46	.91	42	28	0.87	37	7	.44
60	8:00 a.m. or 4:00 p.m.	0.500 00	.76	38	.89	34	24	0.83	28	6	.35
65	7:40 a.m. or 4:20 p.m.	0.422 62	.70	30	.86	26	20	0.78	20	6	.26
70	7:20 a.m. or 4:40 p.m.	0.342 02	.61	21	.83	17	16	0.70	12	5	.17
75	7:00 a.m. or 5:00 p.m.	0.258 82	.48	12	.78	10	12	0.58	6	4	0.10
80	6:40 a.m. or 5:20 p.m.	0.173 65	.31	5	.69	4	..	....	..	..	....
85	6:20 a.m. or 5:40 p.m.	0.087 15	.12	1	.47	0	..	....	..	..	....
90	6:00 a.m. or 6:00 p.m.	0.000 00	0.00	0	0.00	0	..	....	..	..	....

* Cosine of the angle of incidence.

** Calculated by Fresnel's reflection formula and assuming 3 per cent absorption by the glass at noon.

*** Figures in column 3 multiplied by those of column 4.

† Figures in column 5 multiplied by those of column 6.

‡ Figures in column 7 multiplied by those of column 9.

¶ Figures in column 11 added to those of column 10. Apparent discrepancies in this column, as in a few cases in other columns, are due to dropping of third-place decimals.

sky would receive 60 per cent of the diffuse radiation. Column *11,* table 4, shows the approximate addition due to diffuse radiation; column *12* the approximate total energy transmitted through the glass absorbed by a black surface underneath. The corresponding external noon radiation would be 1.00 for direct radiation plus 0.10 for diffuse radiation, giving a maximum of 1.10 total impinging short-wave energy.

At 60° or 2 hours before sunset a fixed glass-covered absorber can receive $\frac{0.35}{1.10}$ or less than $\frac{1}{3}$ the total noon maximum, although the brightness of the direct sunshine has decreased only to $\frac{5}{6}$. Horizontal absorbers have lower midday ratios but differ little from sloped absorbers as the sun approaches the horizon.

If column *12* is multiplied by the observed noon maximum direct intensity (as indicated in table 1), the approximate short-wave input can be calculated, assuming no dust on the glass or absorber surface. Not all the energy received can be converted immediately into useful heat. There are large heat losses from the glass and structure when the latter are hotter than the outside air, and heat absorption by the structure and insulation delays and flattens the useful-heat curve in comparison with the input (fig. 12).

THE SOLAR WATER HEATER

Many persons living in the interior valleys of California, where daily sunshine is dependable for six or seven consecutive months, have found solar heaters satisfactory and economical for supplying hot water. Although many heaters are homemade there are also a large number of commercial manufacture.

The average household needs much water at temperatures of 100° to 140° F, and more would be used if the cost of heating could be reduced. Dairies, schools, and manufacturing plants also use much water heated to temperatures well below that obtainable with fixed solar heaters.

The University of California receives numerous inquiries regarding the construction and performance of solar heaters. Earlier studies of the problem of securing satisfactory performance at low cost with this type of equipment were made in 1927 by Farrall, as reported in Bulletin 469.[7] Increasing use of solar water-tank heaters, together with numerous difficulties with thermosiphon circulation in pipe absorbers, and growing interest in the use of solar heat absorbers in combination with automatic water heaters led to the experiments and investigations reported herein.

GENERAL CHARACTERISTICS OF SOLAR-ENERGY ABSORBERS

Solar energy is used for many different purposes, for each of which a characteristic type of apparatus has been developed. The "burning glass" is an ancient method of converging the sun's rays to obtain temperatures high enough to start combustion. The modern apparatus for producing extremely high temperatures, as developed by the Zeiss Works in Germany, includes a 100-inch searchlight mirror which converges the sun's rays to ⅜ inch where a temperature of 6,300° F is reached in about 30 seconds.[(11)] This pure thermal energy is useful for melting solids in a vacuum. Large parabolic cylindrical reflectors are used to generate steam for a pumping plant in Egypt where the high cost of fuel justifies the alternative extra expense of a solar-power plant. In 1913 this solar-power plant produced 12 pounds of steam per hour per 100 square feet of interception area.[(5)] At the other extreme a dehydrator operator near Davis, California, draws his replacement air through about 200 feet of idle 8-inch irrigation pipe laid in the sun, to reduce his heating cost.

Apparatus for utilizing solar energy for heating water to the moder-

[7] Farrall, A. W. The solar heater. California Agr. Exp. Sta. Bul. 469:1–30. 1929.

ate temperatures required for domestic use has proved economical in comparison with other heating methods in California, and many different types of solar water heaters have been developed.

Exposed-Tank Solar Water Heater.—Simple, bare water boilers mounted outdoors where they will not be shaded have long been used during the summer for furnishing late afternoon hot showers. The tanks are usually horizontal or vertical, but experiments described later indi-

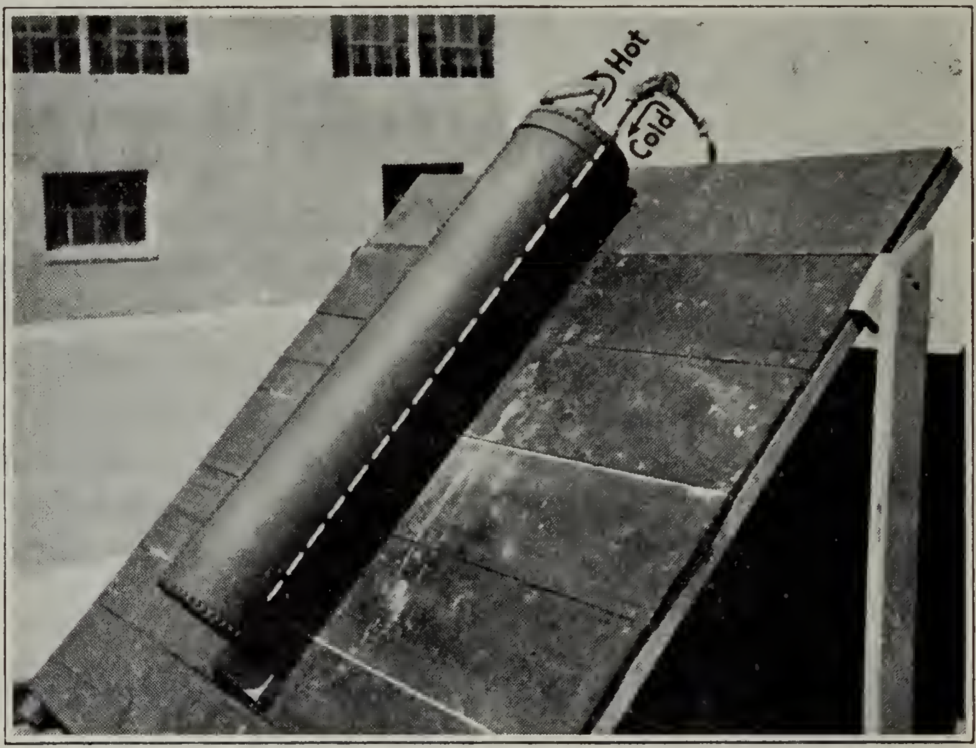

Fig. 6.—Exposed bare tank suitable for heating water for late afternoon shower baths on hot, clear days.

cate that sloped mounting (fig. 6) is more effective. These exposed tanks cool nearly to air temperature at night and are useless before noon.

Enclosed Multiple-Tank Solar Water Heater.—An improvement of the inexpensive exposed tank heater is seen in figure 7. From several tanks enclosed in an insulated, glass-covered box, a large supply of water above 120° F can be obtained in the afternoon. This system might be used for general domestic hot water if the clothes could be washed in the late afternoon when the water is hottest. During the night the water cools off so rapidly that morning temperatures are too low for clothes washing, though it yet might serve for all the other needs. The sunshine falling in the box space between the tanks and on each side indirectly furnishes extra heat for the tanks by convection of hot air. Although the daytime thermal efficiency of the glass-covered tank heaters is high, the large losses at night make the 24-hour efficiency less than for pipe absorbers with insulated storage tanks.

Fig. 7.—Triple-tank absorber in insulated box with hotbed sash cover.

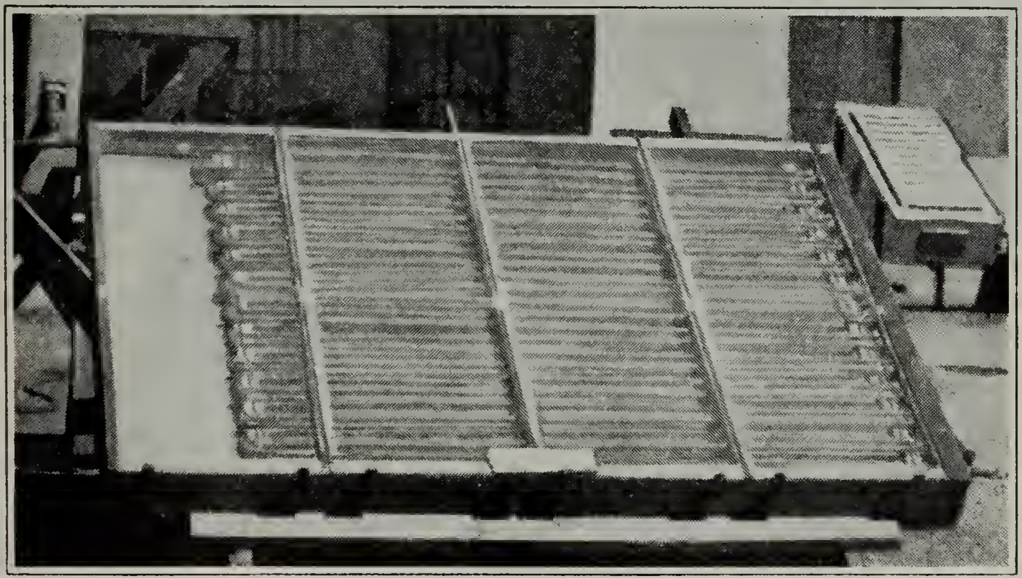

Fig. 8.—Single-pipe solar-energy absorber for small installations. A black background and proper length of box as seen in figure 9 are recommended instead of the experimental reflector-bottom shown in this photograph.

Single-Pipe Absorber with Storage Tank.—The usual "solar heater" consists of a flat, glass-covered, zigzag pipe-coil absorber connected for thermosiphon circulation with an insulated storage tank (fig. 8). In this system when the storage tank is above the absorber there is no appreciable reverse circulation at night, and the high daytime temperature is conserved by the tank insulation so that temperatures over 140° F are available at all times if the system is properly designed.

Multiple-Pipe Absorber with Storage Tank.—When the required absorber area is too large for a single zigzag pipe, the flow resistance can be decreased by installing several pipes in parallel (fig. 9). The heat

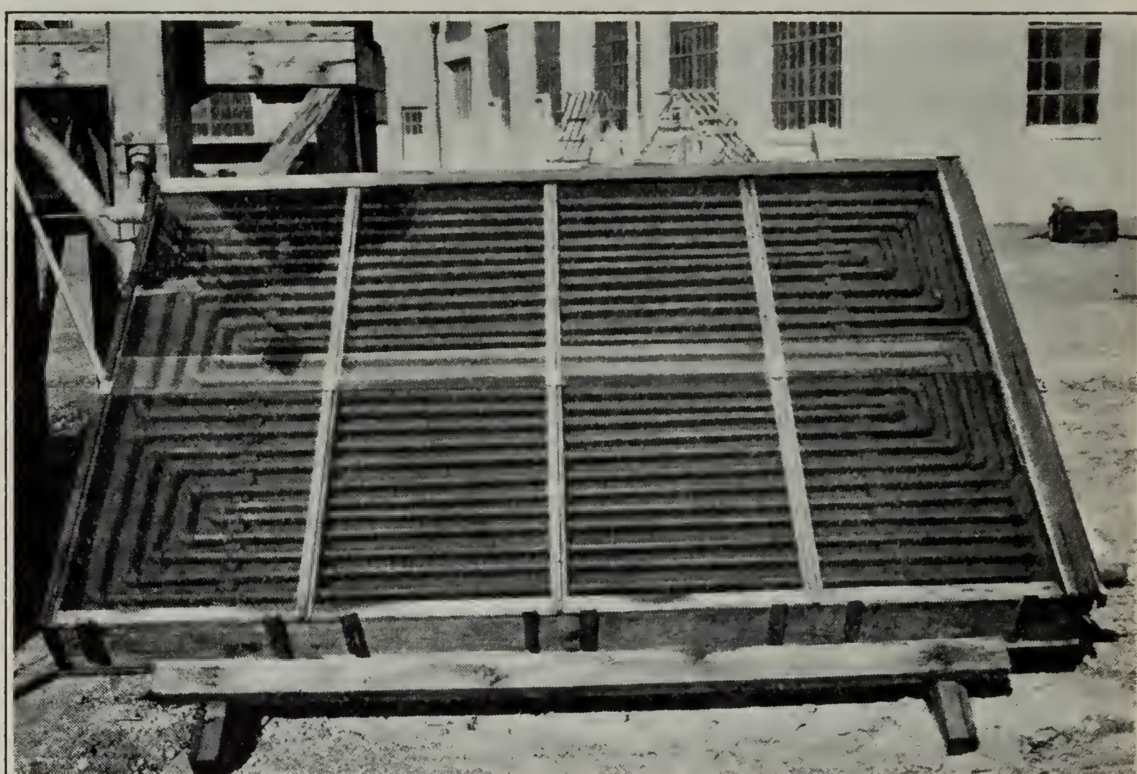

Fig. 9.—Multiple-pipe solar-energy absorber, showing branch-tee method of connecting parallel pipes.

transfer operation is more effective than for the single-pipe absorber of the same area because with the faster flow the temperature rise will be less and the heat losses from the absorber lower.

Ideal Thin, Flat-Tank Solar-Energy Absorber.—Although some of the solar energy falling in the space between pipes can be utilized indirectly by convection of hot air, or by conduction through a cement bed, or by extended fin surface, the ideal absorber has a continuous black surface covering a thin sheet of water. This type is seen in the center of figure 11. The inherent disadvantage of the flat tank is its inability to withstand even low water pressures without an expensive construction using heavy plate and many staybolts. Its high efficiency, due to mini-

mum heat losses, is usually not economical in comparison with a larger, less efficient pipe absorber.

Nonfreeze Solar Water Heaters.—When it is desirable to operate a solar water heater on bright days during the winter, the danger of bursting absorber pipes during cold nights can be avoided by separating

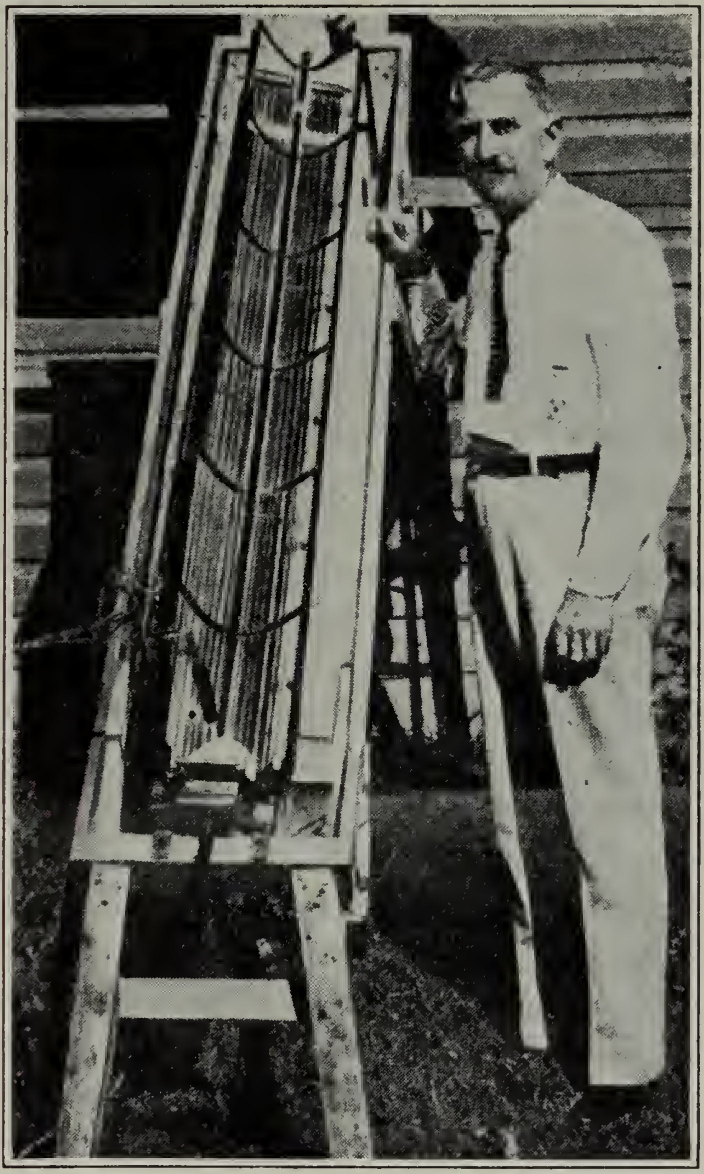

Fig. 10.—Dr. Abbot and his solar power unit for high temperatures. The parabolic mirror appears black because of reflecting the central heat-absorbing pipe.

the absorber circulating fluid from the usable water in the storage tank, and using a nonfreezing solution in the absorber circuit. Figure 23 shows a commercial storage tank with separate heating-fluid jacket which is the only significant difference from the ordinary system of pipe-coil absorber with circulation directly through the storage tank. Standard tanks with internal heating coils or with external heat exchangers might also be used.

Steam Generators and High-Temperature Absorbers.—Figure 10 shows a parabolic reflector-type, high-temperature, solar-energy absorber developed by Dr. C. G. Abbot.[8] The patented unit shown develops about $\frac{1}{6}$ horsepower and can be used for steam generation or, with a special circulating fluid, can be used for heating baking ovens to temperatures of 350° to 400° F. This type of absorber is also suitable for using solar energy for heat-operated absorption refrigerators. Both the two-hour and the continuous heater refrigerators require a minimum working fluid temperature of 250° F, and 325° F is desirable for freezing ice cubes. The reflector used by Dr. Abbot is Alcoa lighting sheet, specular finish, No. 24 gauge, 24 inches × 72 inches, costing about 30 cents per square foot in small lots. The two concentric glass tubes with vacuum between them are on the reflector axis fixed parallel to the earth's axis of rotation. The reflector is rotated about this axis following the sun so that the sun's rays are always concentrated on the central tube.

HOT-WATER DEMAND

The decision as to the kind, size, and system of solar water heater to be installed depends upon several interrelated factors. The nature of the hot-water demand is, of course, the primary question. This demand involves temperature, quantity, and time of day; it varies widely in individual cases, because of differences in personal habits, plumbing facilities, and the relative expense of heating water.

Temperature of Hot Water Needed for Various Domestic Purposes.—The desirable temperature of water used for various purposes is known within reasonably close limits. The temperature data in table 5 were observed in common domestic practice. The water for a hot shower is definitely too hot at 105° F and verges on the cool at about 90° F. Dishwater at 120° F requires the use of a mop because it is too hot to keep the hands in; and although dishes can be scrubbed clean in cold water every housewife would object to dishwater below 105° F. Assuming the usual temperature of the supply water to be 60° to 70° F, the difference in the amount of heating required to obtain the upper and lower limits of temperature is only about 25 per cent.

Quantity of Hot Water Needed for Various Purposes.—The variation in quantity of water used, however, is so great that no average assumption can be considered narrowly. If unlimited inexpensive hot water is readily available at the turn of a faucet, its use will be almost extravagant; the water will be left running while one is doing short chores, tubs will be filled to overflowing, showers will be run to heat bathrooms, and so on. If, on the other hand, a person must wait while water is being

heated or must make an effort to obtain hot water or finds that hot water is expensive, he naturally will use a minimum. The quantity of hot water obtainable from a solar heater varies with the amount of sunshine available; and to make up a deficiency by starting an auxiliary heater involves a time delay, personal effort, and expense so that the natural use tends to follow the available supply. This elasticity of demand greatly extends the period of usefulness of solar water heaters both before the long cloudless summer and afterward into the autumn, often until a water coil in the range or furnace can be depended upon during the winter (fig. 19).

Despite the inherent variations in personal habits one must assume some average hot-water demand in order to estimate the size of water heater that will give adequate service without being unduly large.

For late afternoon hot showers for field workers, a temperature of 102° F is needed, and a minimum quantity of 12 to 15 gallons per person. This is usually obtained by simple water tanks exposed to the sun (fig. 6).

For general domestic purposes the average rural demand is usually considered approximately 40 gallons of hot and cold water together per person per day, of which one-third is assumed to be heated. The American Society of Heating and Ventilating Engineers recommends an estimate of 40 gallons of hot water per person per day for apartment houses. This difference of 3 to 1 is due largely to the convenient availability of hot water in apartment houses equipped with steam boilers operated by a janitor.

The data in table 5 were obtained by J. R. Tavernetti from a test installation of a low-wattage electric water heater for the California Committee on the Relation of Electricity to Agriculture. These metered observations covering the daily springtime routine for a family of two adults, two small children, and a baby give a direct intermediate example of hot-water use when an adequate supply is always available from a solar heater operated in series with an automatic electric water heater, which was considered expensive to operate. All figures include the quantity wasted in warming approximately 40 feet of cold pipe.

If the family is considered as equivalent to four or five adults, the average total daily hot-water demand is approximately 20 to 25 gallons per person. This figure, though much greater than the accepted rural average, is only 50 to 60 per cent of the demand recommended by the American Society of Heating and Ventilating Engineers for apartment houses. Nevertheless, the observed total coincides with the general recommendations of a manufacturer of commercial solar water heaters.

Recognizing that the figures in table 5 represent neither a scanty nor an extravagant use of hot water, one notes that 58½ gallons of hot water is needed in the first 3 hours on wash days (3 times a week); then only 14½ gallons is used in the following 5½ hours, with no demand at all for the next 3½ hours. Then another heavy demand of 49½ gallons of hot water comes with the evening baths, usually within 3 hours. Obviously, the solar heater cannot meet the first demand of 60

TABLE 5

Daily Hot-Water Demand for a Family of Five

Time	Use	Temperature, degrees F	Quantity of hot water, gallons
7:00 a.m.	Shaving and incidental	100	4, plus cold blend
8:00–8:30 a.m.	Clothes washing, one machineful re-used	128	14
8:30–9:15 a.m.	Dishwashing	128	12
9:30 a.m.	Washing clothes by hand in sink	120	3½, plus cold blend
9:15–10:00 a.m.	Four trays rinse water	100	22, plus cold blend
10:00 a.m.	Baby's bath	100	3, plus cold blend
10:15–11:30 a.m.	Incidental	...	3
11:30 a.m.–3:30 p.m.	Washing dinner dishes and incidental	125	11½
7:00–7:30 p.m.	Two children's baths	92	25, plus cold blend
7:30–8:30 p.m.	Washing supper dishes	125*	7
8:30 p.m.–6:30 a.m.	Two adults' baths	95	17½, plus cold blend
	Wash-day total		122½ gallons hot water
	Average daily total		96 gallons hot water

* An electric dishwasher requires 150° water to sterilize, but water 160° F or hotter causes trouble. The total quantity including the preliminary spray (waiting for water to run hot) averages 5 or 6 gallons per charge. Usually an additional 3 gallons is used simultaneously for washing pans and for incidental cleaning-up.

gallons early in the morning without an insulated tank to keep hot the water heated the previous day. Since, furthermore, the evening baths will be taken from this storage of hot water needed in the morning, the storage tank should be large enough, as a general rule, to hold the entire day's requirement.

Quantity and Temperature of Hot Water Needed for Farm Dairies.—For farm dairies (up to 60 cows) the hot-water demand is approximately 10 gallons twice a day at 120° F for washing utensils; but steam (about 35 pounds per day) is also required for sterilization; and both, of course, are needed every day regardless of the weather. Steam can be generated by specially designed solar heaters (fig. 10), but since an auxiliary boiler is required for cloudy days, the investment in a special solar heater for steam generation would be warranted only if the cost of fuel is exceptionally high. Dairies producing milk to be used for manufacturing purposes can manage with hot water alone if at 180° F. This temperature is obtainable with well-insulated double-glass pipe absorbers and might be cheaper than the fuel used in the auxiliary heater.

EXPERIMENTAL INVESTIGATIONS

The useful heat output of a fixed solar-energy absorber depends primarily upon the short-wave energy received, which changes rapidly during the day and differs from day to day because the intensity of the sunshine varies with the season and with the character of the atmosphere. Second, the useful heat output is affected by the heat losses of the absorber, which vary with temperature and wind. No single-day

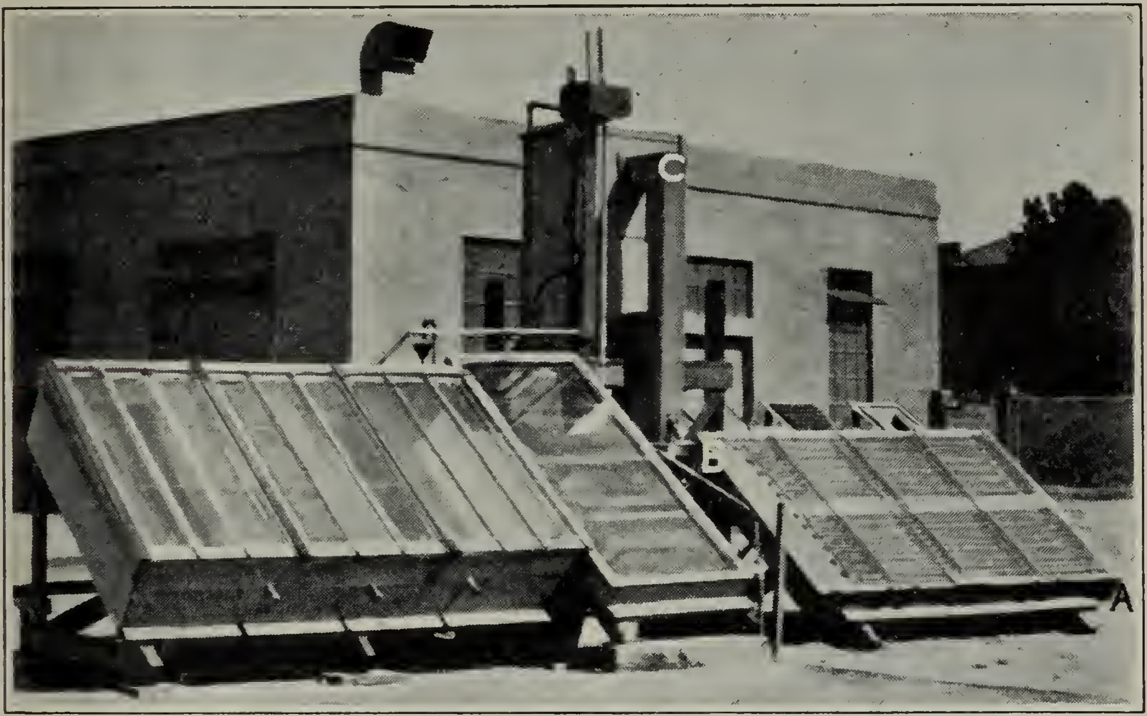

Fig. 11.—Three experimental solar water heaters with elevated storage tank. At the left is the enclosed triple-tank heater shown in figure 7. In the center is the thin flat-tank absorber used for reference. At the right is a pipe-coil absorber (also shown in figure 8) with connection at *A* from the bottom of the storage tank. Above the pipe-absorber outlet *B* there is an insulated vertical riser to *C*, where it turns to enter the top of the storage tank.

figure or curve, therefore, can be a standard. In order to compare the results of different experiments on different days, three different types of heaters were built by Charles Barbee and H. D. Lewis (fig. 11). Simultaneous observations were made throughout the late summer and fall and are discussed in the following sections.

Heat output of Thin Flat-Tank Absorber.—Figure 12 indicates the useful heat obtainable on clear days near the end of the usual solar-heater season. Midsummer values would be much higher. The data for this curve were obtained with water constantly flowing through a flat, thin tank 20.9 square feet in area with a single-glass cover, as shown in the center of figure 11. The rate of flow was maintained constant at

about 1 quart per minute by gravity from the float chamber seen in figure 11, above and to the left of *C*. The discharge was into an open funnel, visible at the upper left-hand corner of the flat absorber. A noon temperature rise of about 40° F above the inlet temperature of about 80° F occurred, and the average absorber temperature was somewhat above average air temperature, as would be the case in a solar water heater. The total useful heat obtained per day, as indicated by the area under

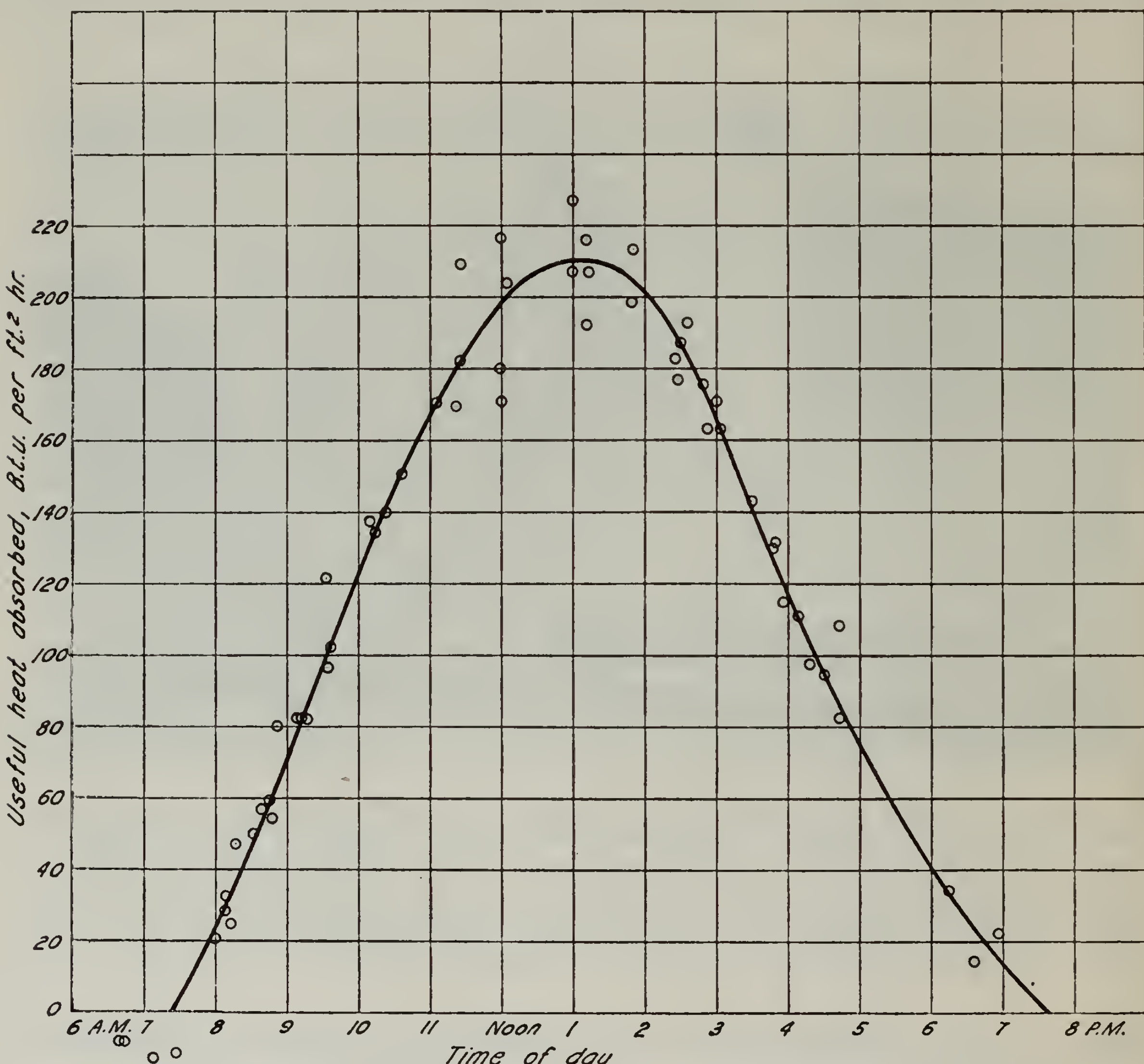

Fig. 12.—Useful heat output of thin flat-tank absorber on clear days, September 23–27, 1935.

the curve of figure 12, was 1,360 B.t.u. per square foot. There are large heat losses from the hot absorber box and considerable heat absorption by the insulation. The latter, though not a true loss, delays and lowers the peak of the curve in relation to the theoretical input (col. *12,* table 4).

Performance Characteristics of Round-Tank Absorbers.—The temperature rise in round-tank absorbers differs from that in thin flat-tank absorbers mainly because of the large water quantity associated with a

given absorber area. The common 30-gallon hot-water boiler 1 foot in diameter by 5 feet long has such a poor ratio of area to volume that the water does not warm rapidly. Since larger-capacity tanks have even poorer ratios of area to volume, and smaller diameter would be special, this study by H. D. Lewis was confined to the regular 30-gallon tanks.

Figure 13 shows the performance of exposed horizontal and sloped tanks which on calm days furnish enough hot water for two or three hot

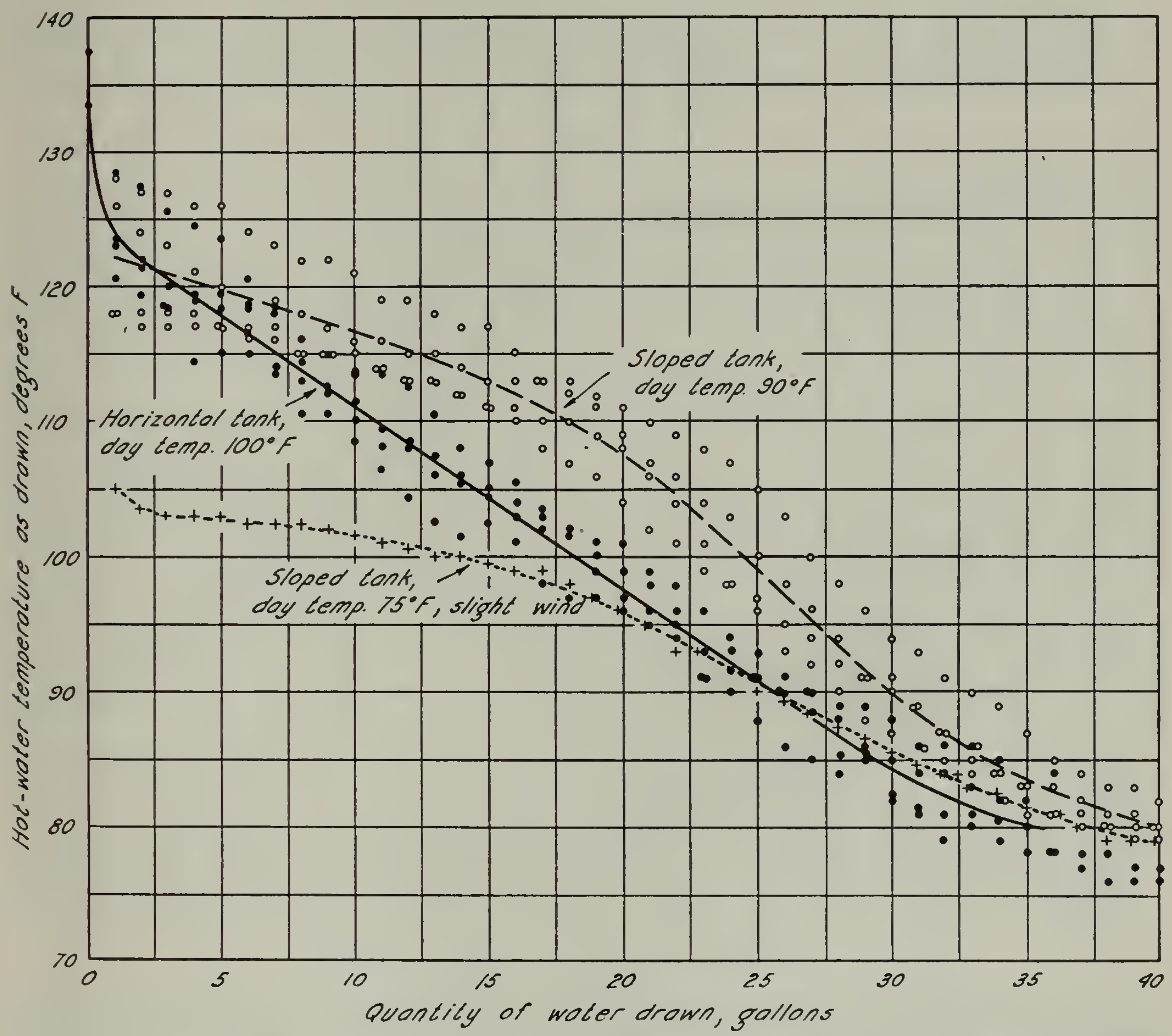

Fig. 13.—Temperature of hot water drawn at 4:00 p.m. from simple uncovered 30-gallon tank in July; temperature readings were taken of each gallon as drawn.

showers at 102° F. The horizontal tank on days with average air-day temperatures of 100° F furnished 20 per cent less hot water than the sloped tank even on days 10° colder. The horizontal tank is less efficient because all the sunshine falls on the hottest part of the tank. If the tank is sloped (fig. 6), the sun shines on the lower, cold end as well as on the upper hot end. In this case much of the colder water is heated directly at low temperature and with small heat loss. In all cases the average water temperature reached its maximum before 4 p.m.

The lowest curve (fig. 13) indicating the heat output on a cold summer day, shows the need for protecting the tank against cold air and wind; but even so there is ample water for one hot shower.

The addition of a simple glass cover supported by an inverted V frame so that the glass formed a coop over the sloped tank resulted in much better performance (fig. 14). The water was drawn three hours

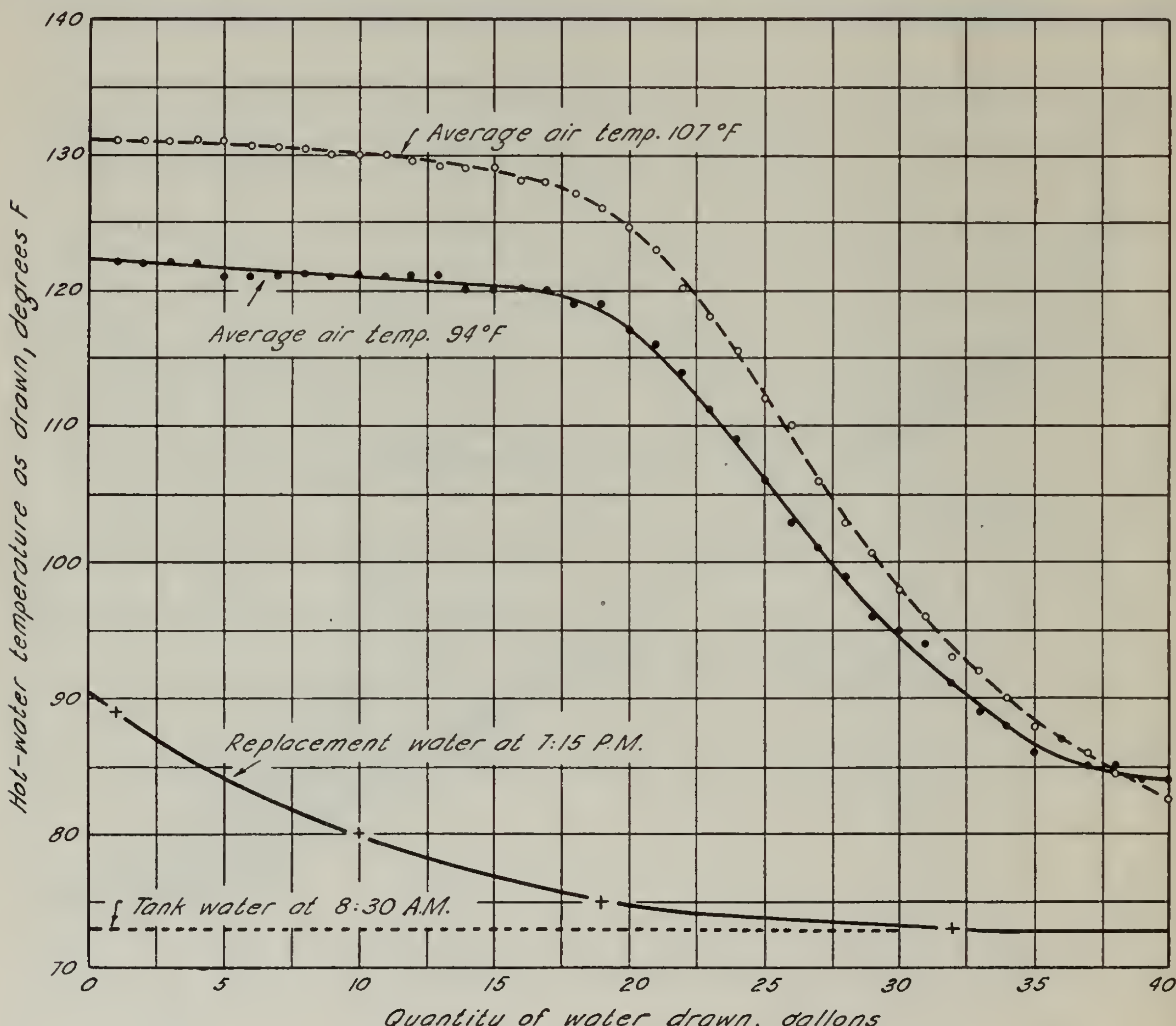

Fig. 14.—Temperature of hot water drawn at 7:15 p.m. from glass-covered, 30-gallon tank without insulation, July 17 and 18, 1935; temperature readings were taken of each gallon as drawn.

later in figure 14 than in figure 13, during which time the air temperature dropped 16° F.

When the quantity of hot water available from a 30-gallon tank heater is not sufficient but the characteristic temperature performance is satisfactory, a larger quantity is obtained by using several tanks in parallel, with all the cold-water inlets connected together in one direction and all the hot outlets connected together in the opposite direction. The tanks should be spaced well apart to avoid the shading of one by another in the early morning and late afternoon.

The tanks in figure 7 were on 24-inch centers, and the inside width of the box was 8 feet.

Performance Characteristics of Enclosed Multiple-Tank Absorbers.—Multiple 30-gallon tanks are easily enclosed in an insulated box and covered with regular hotbed sash. Although temperatures over 140° F are obtainable in the late afternoon, the morning temperature cannot be expected to exceed 110°, which is too cold for washing clothes. This system (fig. 7) has, however, the advantage of simplicity, high daytime efficiency, and self-storage, and is nonfreezing in most of the agricultural areas of California.

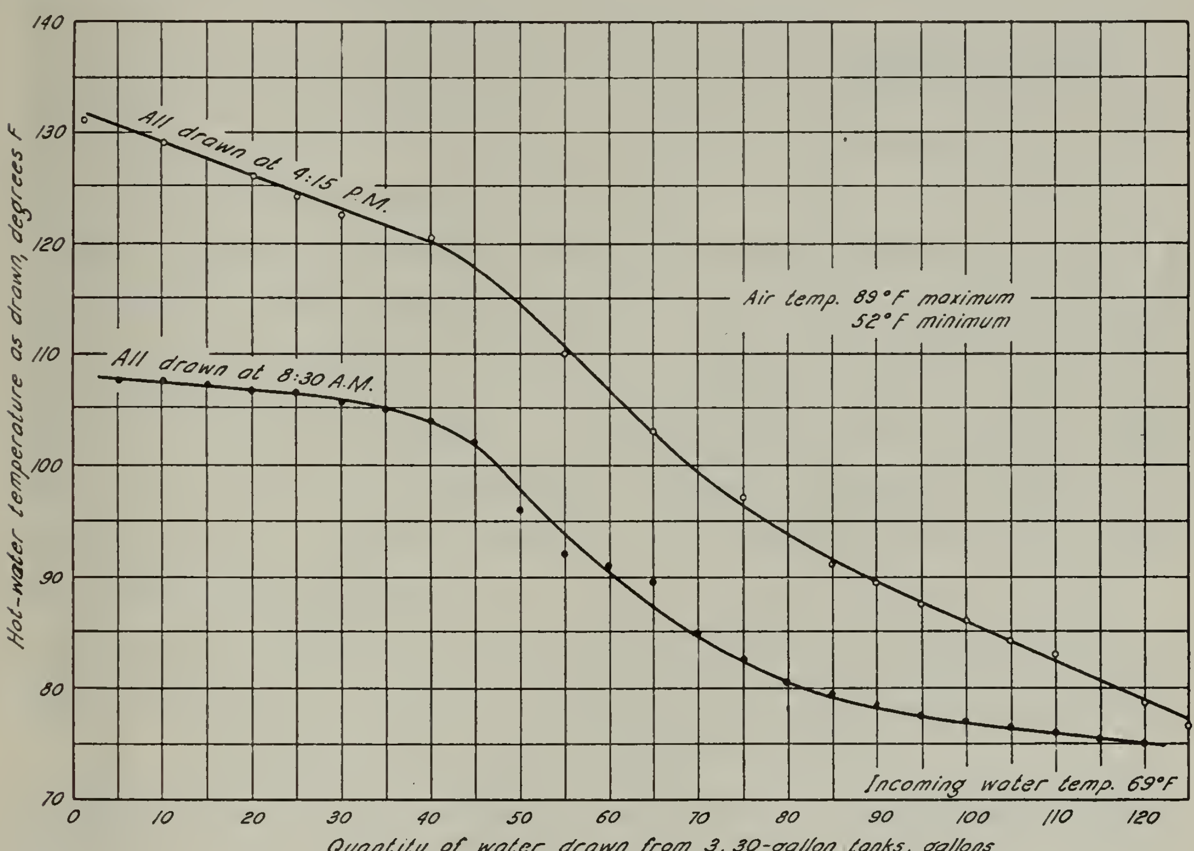

Fig. 15.—Temperature of water drawn from enclosed triple-tank absorber, after one day's heating, at 4:15 p.m. and 8:30 a.m., September 11 and 12, 1935; temperature readings were taken of each 5 gallons as drawn.

Figure 15 shows the performance of three enclosed tanks connected in parallel. The tanks had been filled at 8:30 a.m. with cold water (67° F). The hot-water output per tank in the insulated box at 4:15 p.m. on September 12 is better than that from the exposed tank in July (fig. 13). Furthermore, the exposed tank cooled nearly to air temperature every night; and although the water temperature in the enclosed tank dropped 25° to 35°, this drop was less than one-half the difference between the evening hot-water temperatures and the morning air temperatures. It is unfortunate that usual methods of insulation will not preserve a tem-

perature the next morning at 8:30 a.m. high enough for efficient clothes washing.

If the three tanks are connected so that cold water enters the two outside tanks and hot water is drawn from the center tank alone, 30 gallons of water drawn at night does not lower the temperature of the center tank appreciably, but during the night the hotter center tank cools more rapidly. Figure 16 shows that this method of connecting the three tanks

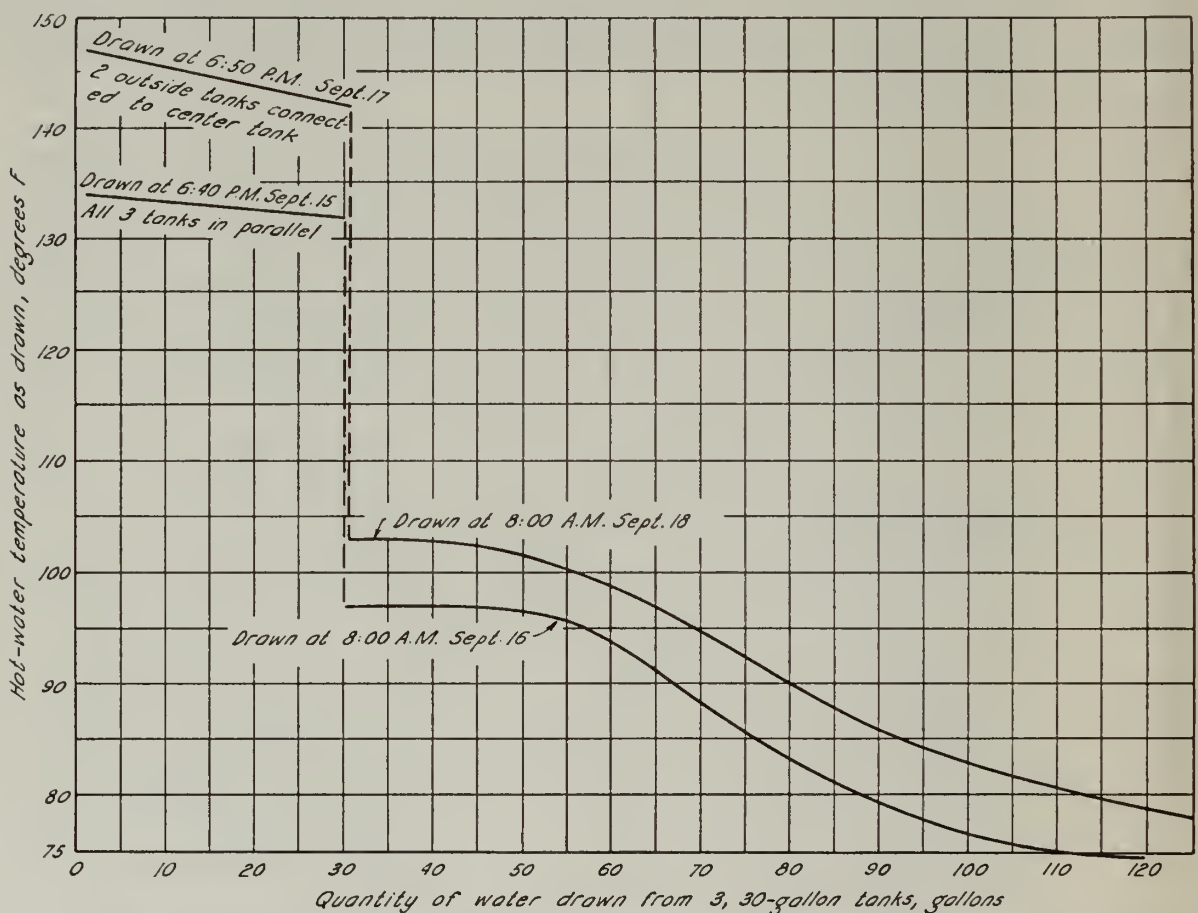

Fig. 16.—Temperature of water drawn, 30 gallons at night and 60 the next morning, from enclosed triple-tank absorber with parallel connection and with cold water connected to two outside tanks and hot water drawn from the center tank; temperature readings were taken of each 5 gallons as drawn.

gives no higher morning temperatures than would be expected from the regular parallel connection. In case of frequent daytime use of hot water there may be some advantage in such a connection, in that it would avoid mixing cold tap water in the center tank, and some saving might be made if the absorber box were partitioned to isolate the hot tank.

The data for figures 15 and 16 were obtained with tin-plate reflectors under each tank so curved that all the incident light was thrown onto the tanks. The entire box appeared black from all angles except at the east and west edges. In November these reflectors were removed, and the entire box was painted black. The useful heat output with or without

reflectors was 724 B.t.u. per day per square foot of glass area. The amount of solar energy received by the thin, flat absorber, was 1,020 B.t.u. during the day the triple tanks had reflectors and 1,003 B.t.u. per sq. ft. during the day the triple-tank box was plain black. This indicates no advantage in using tin-plate reflectors in an insulated box. The general results of all comparisons between the enclosed triple tanks and the ideal thin, flat-tank absorber indicate an approximate relative efficiency of 70 to 75 per cent for daytime heating.

Thermosiphon Circulation and Temperatures in Pipe Absorber with Storage Tank.—The faults of the round-tank absorbers—namely, small absorption area in proportion to the tank capacity, and large nocturnal losses—are remedied by separating the storage tank from the absorber area. The absorber area can then be designed to satisfy the heat requirements independently of tank size; and the storage tank, being separate, is easily insulated to minimize heat losses.

The separation of absorber and storage tank requires some means of heat transfer from absorber to tank during the day and the prevention of heat loss from tank to absorber during the night. This transfer can be accomplished positively by forced circulation, using a positive pump that is operated only during the heating period. For domestic installations this system is objectionable because of expense, leaky packing glands, and the need for mechanical or electrical power not directly available from sunshine.

Solar heat itself is, however, available upon absorption by the water for producing thermosiphon circulation if the piping system from tank bottom to absorber and back to tank top is properly designed. Water warmed in the absorber becomes of lower density than the colder water in the pipe from the tank bottom, which will flow into the absorber and push the heated water into the top of the tank. The force available for this circulation is proportional to the difference in density of the hot and the cold water (table 7).

If the absorber is well below the tank, it becomes a low, cold pocket at night and thermosiphon circulation ceases. The night losses are thus confined to the escape of heat through the tank insulation and to the cooling of the absorber unit, which contains but little water.

The rise in temperature of the water in the absorber pipe due to the sun's heating depends primarily upon the length of time the water remains in the absorber pipe. These factors act together so that an automatic balance exists between the pipe friction and the force available from the difference in water density due to heating. If the sunshine suddenly becomes more intense, creating an excess in temperature differen-

tial, the increased difference in water density provides more force to make the water flow faster; and then it will be in the absorber for a shorter time and will be warmed to a lower degree, thus balancing any temporary temperature excess.

Figure 17 shows the observed temperature differentials and rates of circulation for a five-pipe absorber connected to a storage tank with the

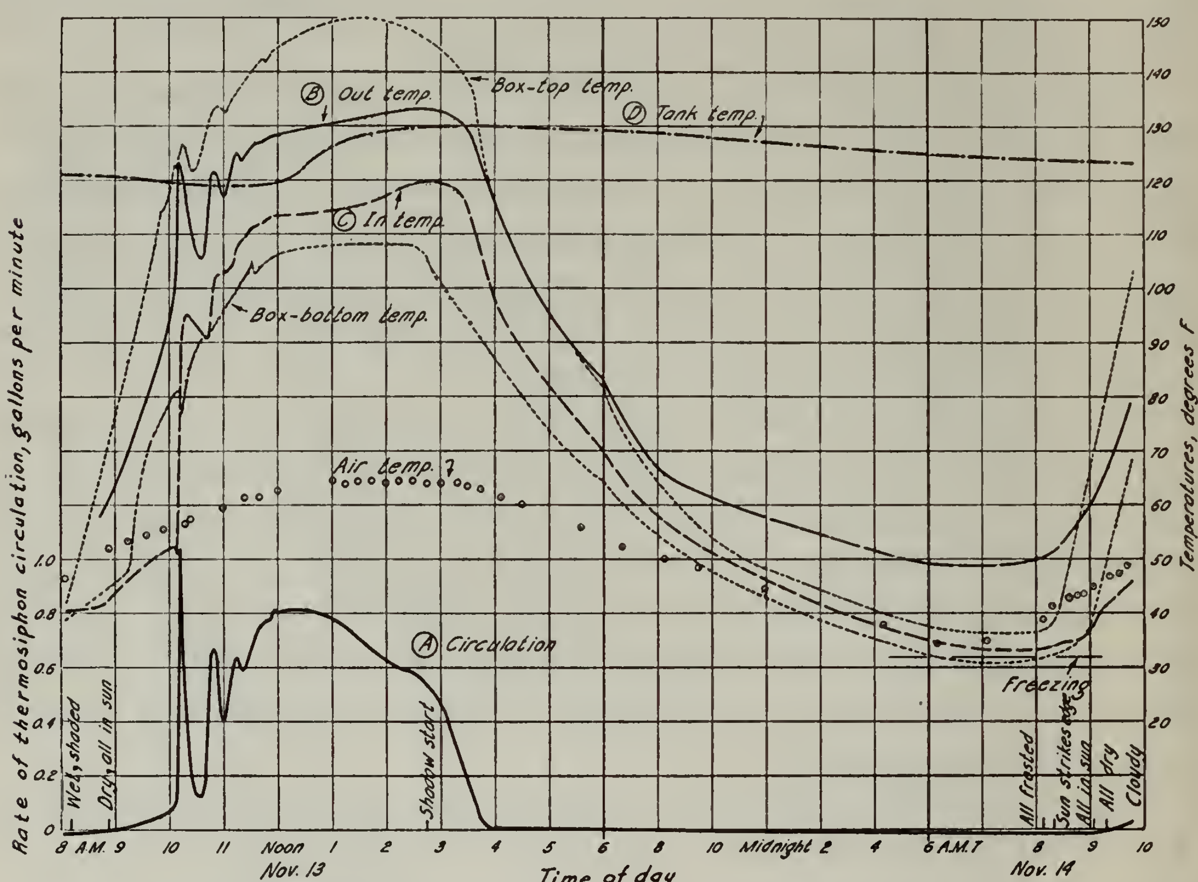

Fig. 17.—Observed temperatures and thermosiphon circulation in a 5-pipe absorber connected with a large storage tank, November 13 and 14, 1935, under a clear sky and light wind.

hot circulation inlet 7½ feet above the center of the absorber. The rate of flow, curve *A*, was determined by the deflection of a vane suspended in a horizontal glass tube, previously calibrated.

Circulation begins slowly at 9 o'clock, gradually pushing the cold water in the vertical riser into the tank. Then suddenly, an hour later, a surge occurs when the hot water, too long in the absorber, fills the vertical riser, while the very cold water due to night cooling still fills the vertical part of the pipe from the tank to the bottom of the absorber; thus a maximum temperature differential is provided. This surge quickly dies away as unheated water rushing through the absorber fills the vertical riser while hot water from the tank is drawn into the vertical drop; thus a temporary minimum temperature difference is created. An-

other smaller surge occurs later for similar reasons, and then, except for a minor surge at 11:15, the circulation builds up steadily to a maximum at noon. It gradually falls off thereafter as the tank water warms up and the solar intensity decreases. The flow stops rather suddenly when the absorber becomes shaded. Because of nocturnal cooling of the vertical riser which enters the tank 4 feet above the pipe to the bottom of the absorber, slight reverse circulation occurs, reaching a maximum about sunrise.

The temperatures of the water leaving and entering the absorber are shown by curves *B* and *C* respectively. These reflect the flow surges previously described. The temperature difference between *B* and *C* does not indicate properly the driving force for the circulation, because of the importance of the water density in the vertical riser shown in figure 11 from points *B* to *C* and in the vertical part of the cold pipe from tank bottom to pipe-absorber bottom at point *A* of figure 11. The relation observed in figure 17 between the outlet temperature *B* and tank-center temperature *D* shows the mutual dependence of the two. This 120-gallon storage should have had an absorber nearly three times as large as the experimental 40.3 square feet, so that the daily rise in tank temperature would be much steeper. Then *B* and *C* would also rise much more sharply during the day because the water will not flow from the absorber into the tank unless the absorber is hotter than the tank. Practically, the tank temperature *D* shown in figure 17 is what might be expected in a full-sized installation when about 100 gallons of hot water is gradually drawn during the day.

The temperatures inside the absorber box at the top and at the bottom are included in figure 17 to indicate the heat transfer by air convection from the black bottom to the pipes. The minimum box temperature was 4° F below minimum air temperature, and the glass was frosted at sunrise although the pipe did not quite reach freezing. This absorber was exposed during the entire winter of 1935–36 at Davis and did not burst although a minimum air temperature of 25° F was recorded. This, however, cannot be considered safe practice.

Relation between Rate of Circulation and Temperature Rise in Different Pipe Absorbers.—The rate of heat input to the storage tank is influenced by the temperature of the tank water, because a high inlet temperature means greater losses from the absorber box. This change, however, is not so important in limiting the maximum storage-tank temperature during nonuse of hot water as is the continual heat loss 24 hours a day from the hot tank and absorber to the colder air and surroundings.

The automatic balance between rate of thermosiphon circulation and temperature rise in the absorber is distinctive for different types of absorbers (table 6). No corrections have been applied to reduce the observations to comparable exposed areas because it is difficult to predict what portion of the increased heat input with larger area would result in larger temperature rise and what portion in more rapid circulation.

TABLE 6

OBSERVED NOON AVERAGE RATES OF FLOW AND TEMPERATURE RISE FOR DIFFERENT FLAT ABSORBERS

Absorber	Length of single pipe, feet	Glass area, sq. ft.	Rate of free flow, gal. per min.	Temperature rise in absorber, °F	Heat absorbed, B.t.u. per sq. ft. min.	Date
Storage tank kept cold at tap water temperature						
Flat-tank..........	8	20.9	0.80	12.5	4.0	Sept. 2
Five-pipe..........	40	40.3	0.65	21.0	2.8	Nov. 5
One-pipe...........	170	36.0	0.20	53.0	2.4	Sept. 23
Storage tank initially hot and allowed to rise in temperature						
Flat-tank..........	..	....	0.78	10	3.1	Sept. 1
Five-pipe..........	..	....	0.80	15	2.5	Nov. 13
One-pipe...........	..	....	0.20	41	1.9	Sept. 18, 25, 26

Common pipe absorbers, utilizing by convectional heat transfer part of the solar energy falling in the space between the pipes, are slightly less efficient than round-tank absorbers, capturing about 60 to 70 per cent as much energy per square foot of glass as the ideal thin, flat-tank absorber. Therefore pipe absorbers should be about 50 per cent greater in glass area than flat absorbers; but this larger size is usually less costly than the thin, flat-tank type.

If the space between the pipes is filled with concrete up to half the pipe diameter, there is considerable gain in useful heat by conduction—sometimes as high as 20 per cent—making the filled multiple-pipe absorber possibly 80 per cent as efficient as the flat-tank.

A flat reflector of tin-plate under black pipes was found to be only 86 per cent as efficient as a black tar-paper bottom at the time of year when the absorber was perpendicular to the sun's rays at noon. At other seasons a flat reflector would be more useful but probably not superior to a black bottom.

The use of a double glass to improve the thermal insulation of the absorber box is not justified for moderate temperatures, since the de-

crease in radiation received due to the extra glass is usually greater than the reduction of heat loss. With high temperatures or where strong winds are prevalent the double glass is often justified.

Size of Absorber in Relation to Quantity of Water to be Heated.—The average daily heat absorption on clear days in September can be judged from the curve of figure 12 to be approximately 1,400 B.t.u. per square foot of glass for a flat-tank absorber. Such an absorber, although most efficient, is not practical because of its tendency to deform when subjected to internal pressure. A larger-area pipe absorber is more economical, and curves in figure 18 show a simultaneous daily heating by pipe absorbers of approximately 1,000 B.t.u. per square foot of glass. If a supply water temperature of 65° F is assumed, each gallon of hot water will require about 700 B.t.u. for heating. The night losses are about 100 B.t.u. per gallon of high-temperature water, making a total daily requirement of about 800 B.t.u. per gallon. As some allowance must be made for dust on the glass and for desired operation when the sky is not entirely clear, an arbitrary figure of 1 square foot of pipe-absorber area per gallon of hot water can be assumed adequate for satisfactory solar-heater operation for seven or eight months of the year in the central valleys of California.

LENGTH OF PIPE RUN FOR SATISFACTORY THERMOSIPHON PERFORMANCE

There is considerable difference in hot-water temperature at the top of the tank when using single zigzag and when using parallel pipe absorbers, especially over a short heating period. With the single-pipe zigzag small quantities of water hot enough for the small demands are available long before the whole tank temperature builds up with the rapid-flow type. Figure 18 shows the storage-tank temperatures reached in one day's heating, contrasting the large-flow, low-degree rise of the five-parallel-pipe absorber with the small-flow, high-degree rise of the single zigzag. The single-pipe curve is as observed September 25 and 27 when hot water was drawn from the top of the tank while new cold water ran in at the bottom. Although some mixing occurs, the curve has a significant shape. The five-pipe data observed November 6 was corrected by the ratio of heat absorbed in the triple-tank heaters on the same days and also reduced to equivalent glass area. Since this absorber area is about one-third that recommended for the 120-gallon storage tank used, all the temperatures are far below normal practice and do not indicate much difference in overall efficiency. The lower-temperature system is more efficient.

Referring to table 6 and considering the effect of doubling or trebling the absorber area to suit the usual domestic hot-water demand, we see that the temperature in a single zigzag pipe two or three times as long as the 170-foot experimental system would produce an excessive temperature rise of the order of 100° F and consequently large absorber

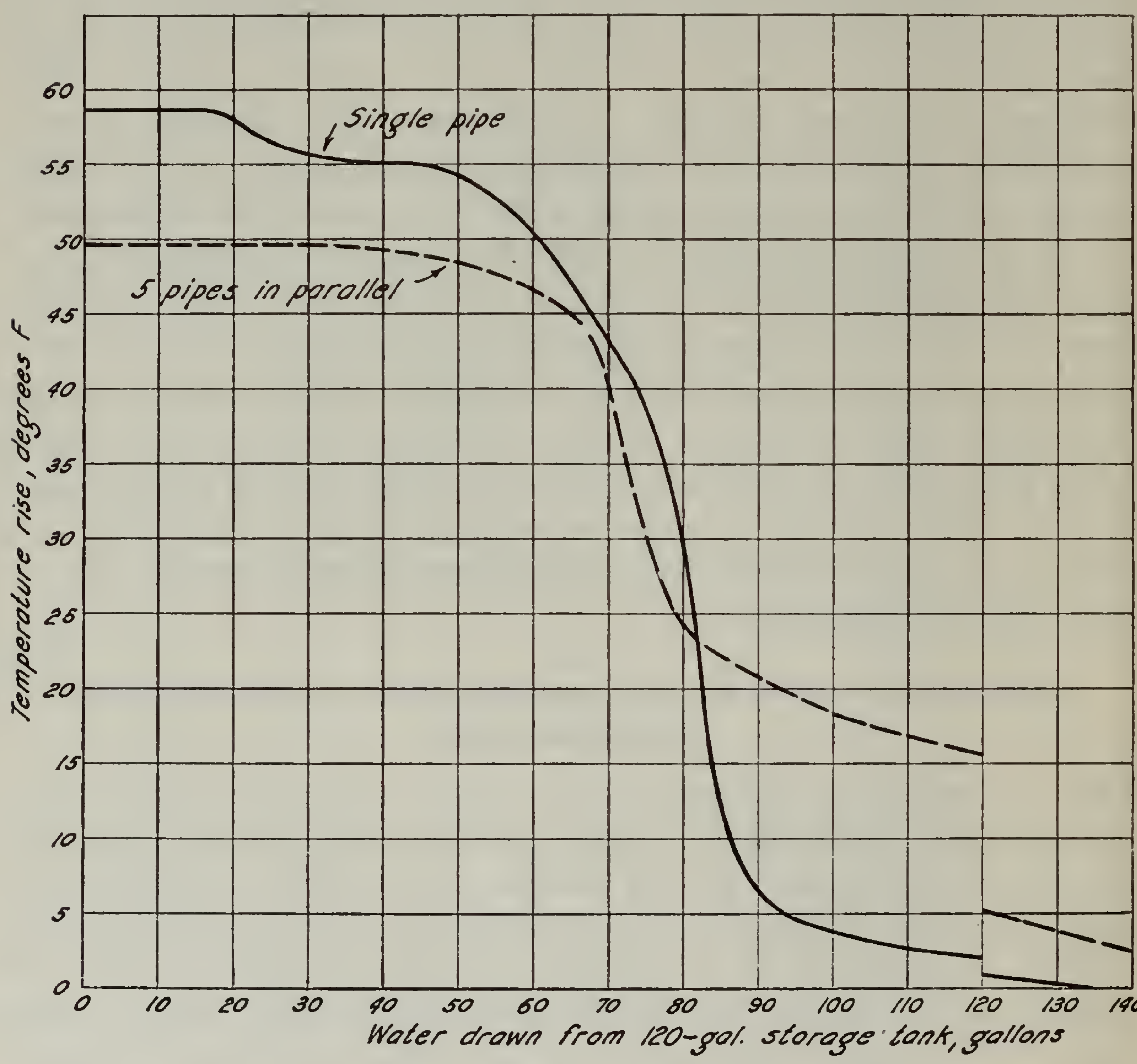

Fig. 18.—Water temperature rise after one day's heating by single pipe and by 5-pipe absorbers connected to an oversized storage tank; readings were taken of each 5 gallons as drawn.

losses to the colder air. If the storage-tank water was initially hot, such a temperature rise would produce boiling in the absorber coils, which is very objectionable. The single zigzag pipe is therefore suitable only for the small 40-gallon systems, and for most solar water-heater systems several pipes should be used in parallel.

Probably at noon a 30° minimum temperature rise is desirable. This could be obtained with single ¾-inch pipes about 70 to 100 feet long when the absorber discharges into the storage tank 7½ feet above the

center of the pipe absorber coils and the pipes to and from the storage tank are 1¼ inch for 3 or 4 parallel pipes and 1½ for 5 or 6 parallel pipes. Large variations will occur, determined by the number of return bends, the height of storage-tank connections, and the weather conditions. When this arbitrary criterion is applied to pipe absorbers containing 4 or 5 lineal feet of ¾-inch pipe per square foot of glass area and per gallon of storage-tank capacity, with the bottom of the tank 2½ feet above the center of the absorber, a 45-gallon system should have three or four pipes in parallel; a 60-gallon system, five or six pipes. In larger systems the storage tank may be raised to obtain greater thermal head. Each pipe run should be about 10 or 15 feet per foot of effective riser height from center of absorber to discharge into storage tank.

In many houses there is no room in the attic above the top of the absorber coils for the storage tank. In such cases a false chimney can be built around the storage tank above the roof. If the storage tank is installed level with the pipe absorber, a thermal valve is required to prevent reverse circulation at night. The low head available for producing thermosiphon circulation calls for larger connecting pipes and also more paralleling in the absorber. An alternative is to use multiple-tank absorbers previously described.

Calculations, following the procedure given in the Chemical Engineers' Handbook,[29] indicate rates of flow approximately twice that observed by means of the vane meter. Special tests at night, when all temperatures were within 1° F and flow was obtained by differential elevation of open inlet and discharge reservoirs, showed the resistance to be higher than calculated and in agreement with the vane-meter thermal-head observations. Comprehensive viscous-flow tests to determine losses in various fittings and short pipe have not been run. Since the rate of flow observed in all the foregoing tests was well within the viscous or laminar-flow region, the resistance to flow was proportional to the viscosity of the water, which, at various temperatures, is given in table 7. The change of viscosity with temperature is rapid, the value near the boiling point being only one-sixth of the value near freezing.

TABLE 7

DENSITY, VISCOSITY, AND KINEMATIC VISCOSITY OF WATER

TEMP.	DENSITY (Weight)	VISCOSITY (Weight)	KINEMATIC VISCOSITY
°F	w, lb/ft³	μ, lb/ft sec	ν, ft²/sec
32	62.418 40	0.0012042	1.929 x 10⁻⁵
33	62.420 57	.0011813	1.893
34	62.422 40	.0011590	1.857
35	62.423 90	.0011368	1.821
36	62.425 07	.0011157	1.787
37	62.425 91	.0010959	1.756
38	62.426 43	.0010763	1.729
39	62.426 64	.0010570	1.693
40	62.426 54	.0010385	1.663
41	62.426 14	0.0010206	1.635 x 10⁻⁵
42	62.425 43	.0010033	1.607
43	62.424 44	.0009863	1.580
44	62.423 15	.0009697	1.553
45	62.421 58	.0009534	1.527
46	62.419 74	.0009375	1.502
47	62.417 62	.0009222	1.477
48	62.415 23	.0009075	1.454
49	62.412 57	.0008930	1.431
50	62.409 65	0.0008787	1.408 x 10⁻⁵
51	62.406 46	.0008650	1.386
52	62.403 01	.0008516	1.365
53	62.399 32	.0008385	1.344
54	62.395 38	.0008257	1.323
55	62.391 19	.0008132	1.303
56	62.386 77	.0008010	1.284
57	62.382 12	.0007892	1.265
58	62.377 23	.0007776	1.247
59	62.372 12	0.0007663	1.229 x 10⁻⁵
60	62.366 78	.0007553	1.211
61	62.361 22	.0007445	1.194
62	62.355 45	.0007339	1.177
63	62.349 45	.0007235	1.160
64	62.343 24	.0007119	1.142
65	62.336 82	.0007036	1.129
66	62.330 18	.0006939	1.113
67	62.323 34	.0006845	1.098
68	62.316 29	0.0006753	1.084 x 10⁻⁵
69	62.309 05	.0006663	1.069
70	62.301 60	.0006575	1.055
71	62.293 15	.0006488	1.041
72	62.286 10	.0006403	1.028
73	62.278 06	.0006321	1.015
74	62.269 83	.0006239	1.002
75	62.261 40	0.0006159	0.989 x 10⁻⁵

TEMP.	DENSITY (Weight)	VISCOSITY (Weight)	KINEMATIC VISCOSITY
°F	w, lb/ft³	μ, lb/ft sec	ν, ft²/sec
76	62.252 78	0.0006081	0.977 x 10⁻⁵
77	62.243 98	0.0006005	0.965 x 10⁻⁵
78	62.234 99	.0005930	0.953
79	62.225 82	.0005856	0.941
80	62.216 47	.0005784	0.930
81	62.206 94	.0005711	0.919
82	62.197 24	.0005645	0.908
83	62.187 36	.0005577	0.897
84	62.177 30	.0005510	0.886
85	62.167 08	.0005444	0.876
86	62.156 69	0.0005381	0.866 x 10⁻⁵
87	62.146 12	.0005317	0.856
88	62.135 40	.0005256	0.846
89	62.124 51	.0005196	0.836
90	62.113 45	.0005137	0.827
91	62.102 23	.0005078	0.818
92	62.090 85	.0005021	0.809
93	62.079 32	.0004965	0.800
94	62.067 63	.0004909	0.791
95	62.055 79	0.0004855	0.782 x 10⁻⁵
96	62.043 80	.0004803	0.774
97	62.031 66	.0004751	0.766
98	62.019 37	.0004698	0.758
99	62.006 92	.0004648	0.750
100	61.994 33	.0004598	0.742
101	61.981 60	.0004549	0.734
102	61.968 72	.0004502	0.726
103	61.955 71	.0004454	0.719
104	61.942 56	0.0004408	0.712 x 10⁻⁵
105	61.929 25	.0004362	0.704
106	61.915 78	.0004318	0.697
107	61.902 17	.0004274	0.690
108	61.888 41	.0004230	0.683
109	61.874 51	.0004188	0.677
110	61.860 44	.0004146	0.670
111	61.846 22	.0004106	0.664
112	61.831 85	.0004065	0.657
113	61.817 36	0.0004024	0.651 x 10⁻⁵
114	61.802 76	.0003984	0.645
115	61.788 05	.0003946	0.639
116	61.773 24	.0003908	0.633
117	61.758 30	.0003871	0.627
118	61.743 25	.0003834	0.621
119	61.728 08	.0003797	0.615

TEMP.	DENSITY (Weight)	VISCOSITY (Weight)	KINEMATIC VISCOSITY
°F	w, lb/ft³	μ, lb/ft sec	ν, ft²/sec
120	61.712 80	0.0003762	0.610 x 10⁻⁵
121	61.697 41	.0003727	0.604
122	61.681 89	0.0003692	0.599 x 10⁻⁵
123	61.666 22	.0003658	0.593
124	61.650 40	.0003625	0.588
125	61.634 45	.0003591	0.583
126	61.618 36	.0003559	0.578
127	61.602 13	.0003527	0.572
128	61.585 76	.0003495	0.567
129	61.569 25	.0003464	0.563
130	61.552 60	.0003433	0.558
131	61.535 81	0.0003403	0.553 x 10⁻⁵
132	61.518 93	.0003373	0.548
133	61.501 97	.0003344	0.544
134	61.484 93	.0003315	0.539
135	61.467 78	.0003286	0.535
136	61.450 51	.0003258	0.530
137	61.433 12	.0003230	0.526
138	61.415 63	.0003203	0.522
139	61.398 05	.0003176	0.517
140	61.380 37	0.0003150	0.513 x 10⁻⁵
143	61.326 4	.0003072	0.501
146	61.271 3	.0002998	0.489
149	61.214 9	0.0002926	0.478 x 10⁻⁵
152	61.157 8	.0002858	0.467
155	61.100 0	.0002792	0.457
158	61.041 4	0.0002729	0.447 x 10⁻⁵
161	60.981 7	.0002668	0.437
164	60.921 0	.0002609	0.428
167	60.859 1	0.0002553	0.419 x 10⁻⁵
170	60.796 3	.0002498	0.411
173	60.732 6	.0002446	0.403
176	60.668 1	0.0002396	0.395 x 10⁻⁵
179	60.602 7	.0002347	0.387
182	60.536 5	.0002300	0.380
185	60.469 6	0.0002254	0.373 x 10⁻⁵
188	60.401 6	.0002210	0.366
191	60.332 8	.0002168	0.359
194	60.262 9	0.0002127	0.353
197	60.192 4	.0002087	0.347
200	60.121 3	.0002048	0.341
203	60.049 4	0.0002012	0.335 x 10⁻⁵
206	59.976 7	.0001976	0.329
209	59.903 0	.0001941	0.324
212	59.828 4	0.0001907	0.319 x 10⁻⁵

Density is interpolated and converted to English units from Int. Crit. Tables, 1928 v III p.27 using multiplier of 62.426 645 (log. 1.7953100)
Viscosity (weight) is interpolated and converted to English units from Smithsonian Physical Tables, 8 th Ed. 1933, p. 205; multiplying centipoises by 0.000 671 97 (log. 6.827 3501-10)

USE AND CONSTRUCTION OF SOLAR WATER-HEATER SYSTEMS

An adequately designed, properly installed solar-heater system will furnish hot water continually throughout the summer in the central valleys of California without an auxiliary heater. The use of an auxiliary heater can be avoided also in the spring or fall if the hot-water demand can be adjusted to the sunshine periods. In the winter, however, some auxiliary water-heating system is desirable. The solar water heater can be used also with an automatic water heater to insure a continual supply of hot water regardless of the weather but at minimum heating cost.

COMBINATION OF SOLAR HEATER AND FURNACE OR RANGE WATER COIL

In the most economical water-heating system (fig. 19), the solar heater is depended upon from early spring to late fall; then, during the winter, the furnace coil or water-back in the range is used for obtaining hot water. If the furnace or range is in daily use, usually the solar heater is shut off and drained to avoid freezing.

Location and Connection of Solar Absorber.—The solar absorber is most conveniently placed on a roof sloping south and in front of attic windows so that the glass cover can be readily cleaned with a hose (attached to the storage-tank drain) or with a mop. The usual absorber construction is similar to that of a skylight, but with a special provision for an insulated pipe outlet at the top that permits a continuous rise in the pipe to the storage tank. This requirement usually interferes with standard flashing practice. A simple method is shown in figure 19; the hot pipe is brought through the end of the absorber above the roof surface and turned to enter the attic through a separate hole higher in the roof, the pipe being insulated and enclosed in a lead sheath under which the rain water can pass from around the top of the absorber. The flashing around the lead sheath where it pierces the roof is separate from the flashing around the absorber box. In an alternative method (fig. 20), the hot pipe leaves the top edge of the absorber through a special box (shown next to the dormer-window wall) running from the roof slope out to the absorber frame, with the roof flashing arranged to drain each way from this obstruction along the top edge of the absorber.

Safe Piping Practice for Furnace or Range Coil.—Valves between the tank and the cold-water supply line and between the auxiliary heaters and the tank are intentionally omitted to avoid danger of bursting. If

a valve were provided in the supply line to the hot-water tank, the tank might be drained to avoid freezing; and later the range or furnace might be thoughtlessly started with all valves closed and result in an explosion. A single valve at the meter, shutting off all the water, is not objectionable, for the cold-water supply is always turned on before one thinks of starting a hot-water heater. If hot-water shut-off valves are to be in-

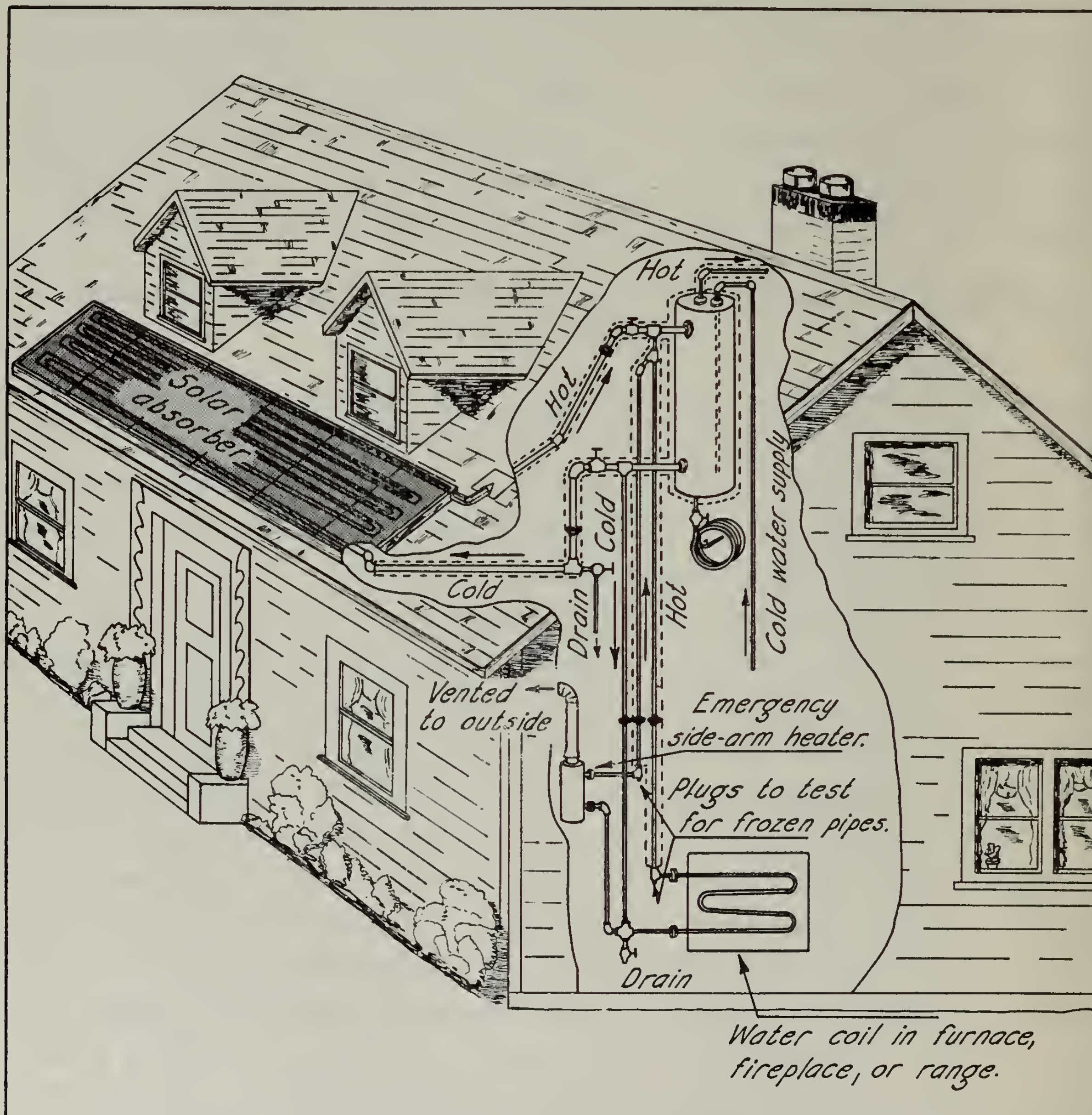

Fig. 19.—Solar absorber and furnace coil with single storage tank.

stalled, recommended dairy sterilizer connection practice should be followed, which specifies a check valve in a by-pass around each shut-off valve so that in case of higher pressures in heaters the water can back up in the supply line even though the manually operated valves are closed. This by-pass and check-valve system permitting reverse flow is alternative to the pressure relief valve, which might not operate properly after long periods of nonuse. By putting a union in the cold-water

line to the solar-heater storage tank near the auxiliary heater, one can easily connect the cold water supply across direct to the auxiliary heater when for any reason the solar storage tank must be removed from the line and the hot-water system promptly restored to operation.

Valves between the solar absorber and the tank are necessary to permit draining the absorber in cold weather without disturbing the rest of the hot-water system. These valves do not create a danger from overheating because the heat losses from very hot absorbers usually balance the solar-energy input at a temperature below the boiling point. If the absorber coils are filled with water that is confined by closed valves, solid expansion by heating might produce serious breaks if there is no entrained air; but this is not so dangerous as the explosion of a closed dry boiler heated by a fire.

Whenever the water freezes in the pipes between the storage tank and furnace or range coil, there is another serious danger of explosion when a fire is started. The use of tees instead of elbows at the upper connections to heating coils makes it easy to inspect by loosening the plugs and draining enough water to notice whether the pressure remains constant.

With gravity-flow water-supply systems, the highest pipe in the solar-heater system must be considerably lower than the bottom of the water-supply tank to insure full lines for thermosiphon circulation.

Installation of Extra Emergency Side-Arm Heater.—The combination of solar heater and furnace or range coil works well in the Sacramento and San Joaquin valleys during the summer and the winter. During a few days in the spring and fall the sunshine is not sufficient to produce water temperatures high enough for clothes washing. On such occasions washing is postponed until the morning following a bright day, or else an emergency side-arm heater (fig. 19) is used.

An extra heater of this type when connected in the furnace coil line often leads to unsatisfactory operation of both heating coils unless the hot-water pipe from each heater is carried separately into the storage tank or connected together very near the tank. This high connection satisfies the requirement that the thermal density differential head in each heater riser be greater in proportion to the total circulation head than the ratio of heater and riser-flow friction to the friction in the complete circuit. One should remember that the flow friction in the heating coil often increases rapidly because of scale formation, thus requiring a higher connection point.

COMBINATION OF SOLAR HEATER WITH AUTOMATIC WATER HEATER

When a continual supply of hot water is essential during cloudy weather and the use of a furnace or range coil is not desirable, an automatic water heater can be installed without sacrificing the advantages of a solar heater.

Two-Tank Combination of Solar and Automatic Water Heater.—The combination of solar heater and auxiliary heater can be made very simply if the tank for the auxiliary heater is separate from the tank for the solar heater. With two tanks both the solar heater and the auxiliary heater can work simultaneously, and an automatic oil, gas, or electric water heater will function only when the water coming from the solar-heater tank is not up to thermostat temperature.

When the solar heater is connected in series with an automatic auxiliary heater (fig. 20), the hot water drawn from the regular heater is replaced by water from the top of the solar-heater tank. On clear days this water will be hot enough already; but if on cloudy days it is colder than the thermostat setting, the auxiliary heater will operate to make up the difference. This combination system insures an adequate supply of hot water, and the housewife will never be bothered by finding the water occasionally only lukewarm.

Storage-Tank Capacity of the Auxiliary Automatic Water Heater.—For the arrangement shown in figure 20, the tank size of the automatic heater need only be adequate to meet sudden demands, though the daily rate of heating water must, of course, be sufficient to provide all the hot water when there is a long period of cloudy weather. According to the demand figures in table 5, if the auxiliary heater is on continuously for 24 hours it must be able to heat at least 5 gallons per hour to provide 120 gallons per day. (Assuming a cold-water inlet of 65° F and a thermostat setting of 145° calling for an 80° rise, a minimum of 3,320 B.t.u. per hour is required. This amounts to only 1 kw. per hour or 4 to 5 cubic feet of natural gas per hour, according to the efficiency of the heater.) If 5 gallons of hot water per hour can be obtained from the heater and 55 gallons is needed within 2 hours, the minimum automatic storage tank size is approximately 45 gallons for the example of small-family routine given above. This example indicates that the automatic heater storage-tank capacity should be about one-half the average daily hot-water demand.

Single-Tank Combinations of Solar and Automatic Water Heaters.—Since two tanks and a connecting line have greater heat losses than a

single larger tank, the thermally ideal combination system is to connect a regular automatic external heater to the top half of a solar-heater storage tank, which is large enough for one day's hot-water demand. The auxiliary heater can be located downstairs (fig. 19) if the thermostat is attached to the center of the storage tank and operates the aux-

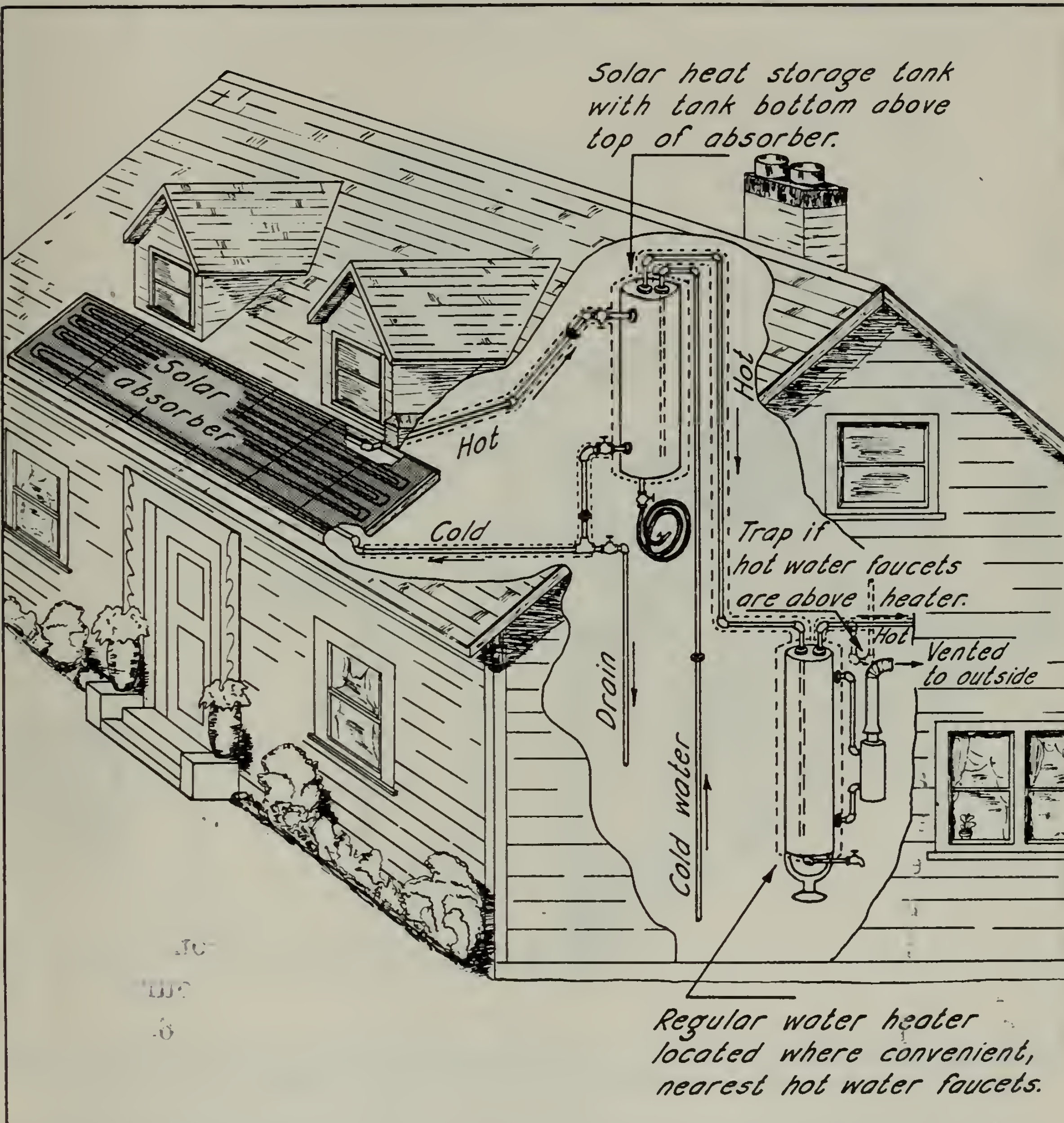

Fig. 20.—Combined solar and automatic water heater with separate storage tanks.

iliary heater by remote control. The solar absorber connection to the bottom half still makes use of the entire tank, but in cloudy weather only the top half will function as a separate automatic storage heater. The connection of the solar absorber to the bottom half of the tank, as shown by full lines in figure 21, is objectionable only in that the maximum solar-heat temperature is not available in small quantities at the top of the tank. This objection is important only when the auxiliary

heater is not in use. The thermal efficiency of the center-inlet-connection type is the same as the top-connection type because all heat absorbed is available in reducing the demand on the automatic heater. It would be a mistake to use an auxiliary heater to warm the entire solar-heat storage tank, because circulation through the solar-heat absorber does not start

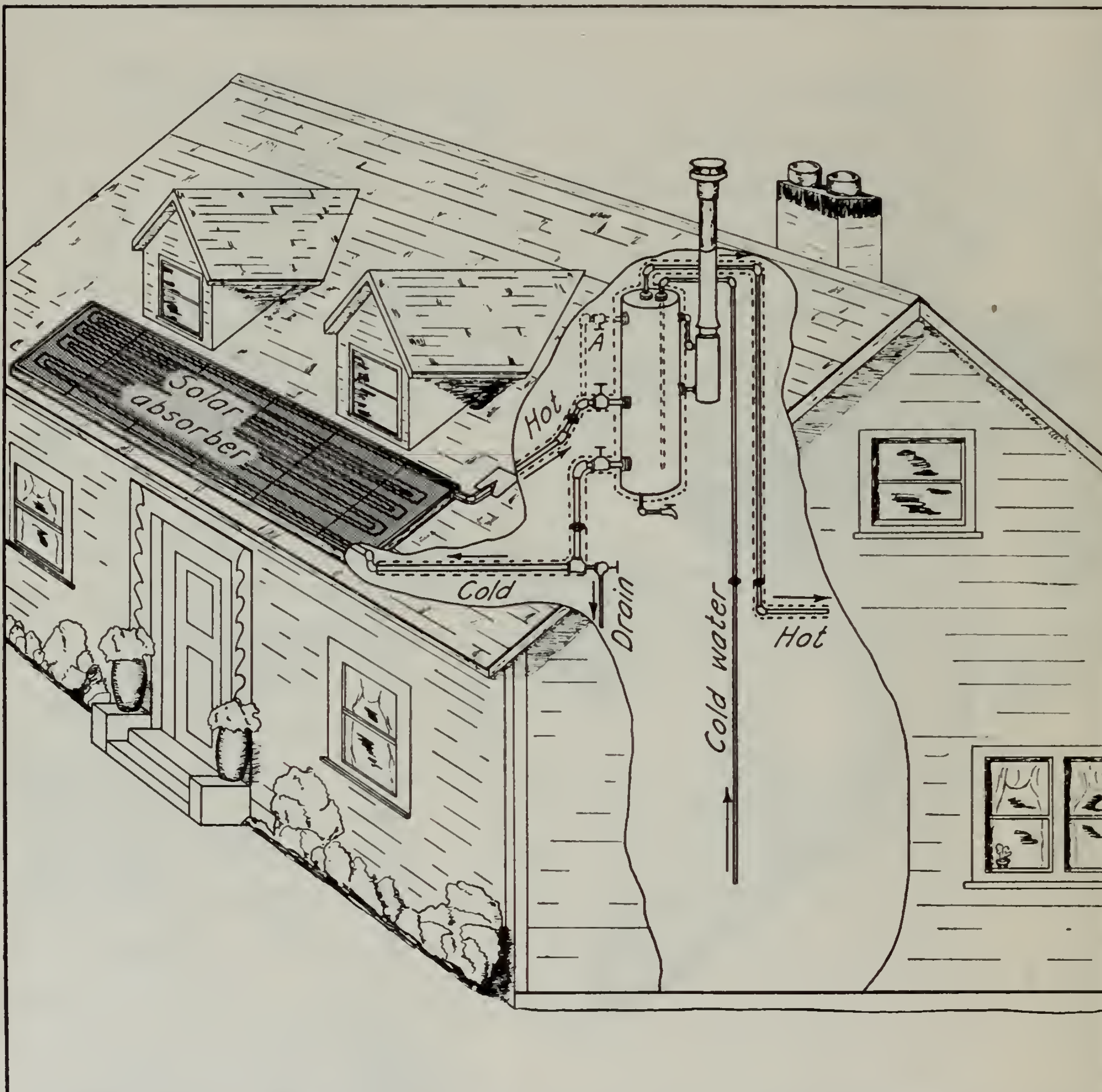

Fig. 21.—Solar absorber and automatic water heater with single storage tank.

until the absorber is hotter than the tank. In cold weather the absorber may never reach thermostat-control temperature but yet may be much hotter than the cold-water supply, which it can warm up when the connections are made as shown in figure 21.

When this single-tank system is to be used with a gas, oil, or coal water heater which should be shut off in good solar-heater weather, the connection of the hot-water pipe from the absorber should go to the top of tank as indicated by the dotted line at *A*. Both connections can be made in parallel, and the top valve opened when the auxiliary heater is not

to be used. There is no loss in efficiency in having both valves open except when the auxiliary heater is in operation.

The main objection to this system, which is useful in the winter, is the danger of freezing the pipe-absorber coils. The simplest way to avoid freezing is to drain the solar absorber on cold nights.

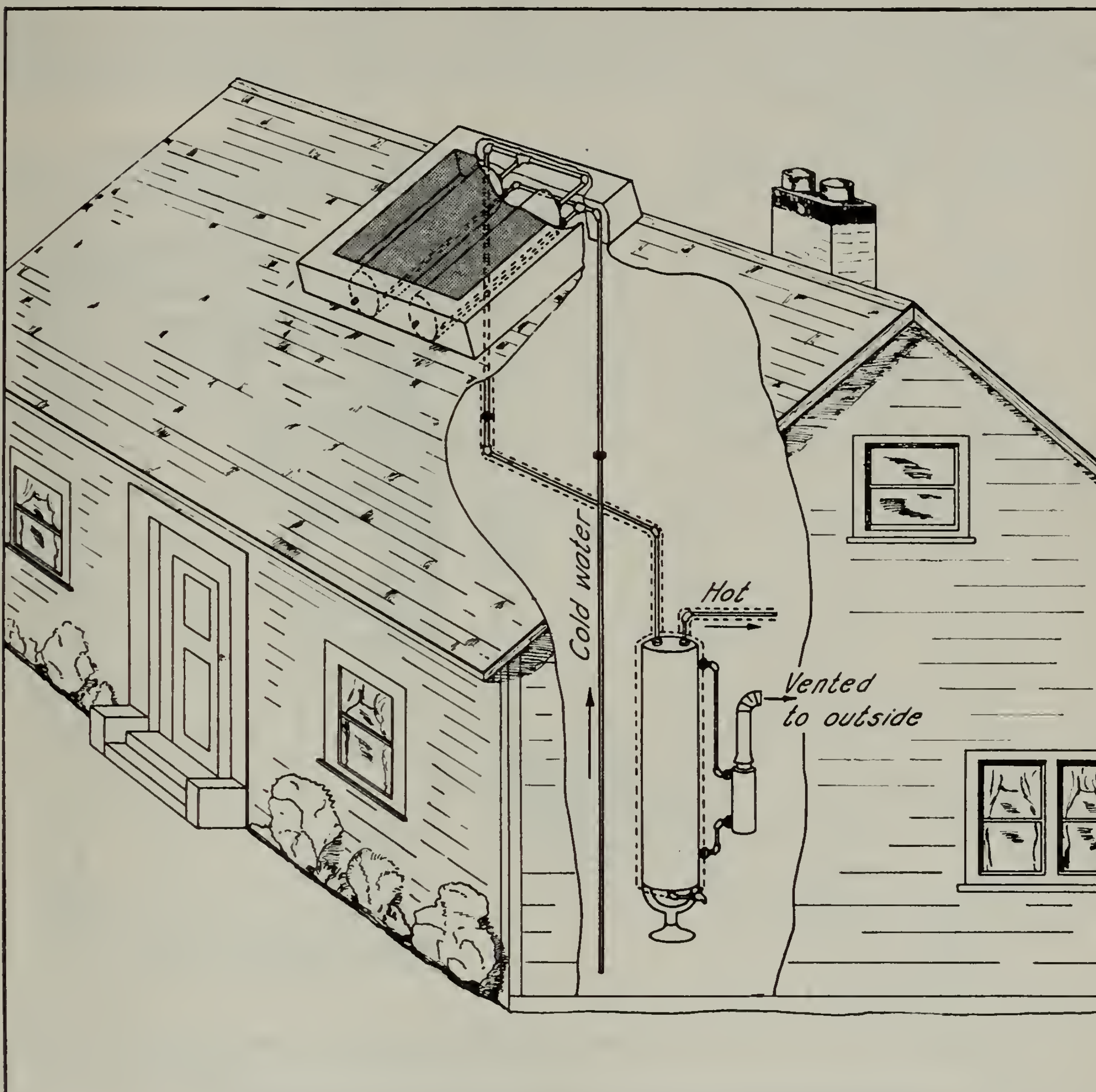

Fig. 22.—Solar double-tank heater combined with automatic water heater.

Solar Tank Heater to Reduce Operating Cost of Automatic Heater.— When an automatic water heater is in daily use and the installation of an adequate solar water-heater system is not feasible, one may utilize solar heat to reduce the operating cost of an automatic water heater by installing a simple tank heater (fig. 7) on the cold-water line between the supply and the automatic heater (fig. 22). This system has the advantages of low cost, simplicity, high daytime efficiency, self-storage, and of being nonfreezing. Two 30-gallon boilers and two 3 × 6 foot hotbed sash cost less than $25 and will absorb at least 20,000 B.t.u. per day

for about eight months; and with an electric water heater on the $1\frac{1}{2}$ cent rate per kw.-hr. they will give a net saving of about $15 a year. This combination avoids the main fault of low morning water temperature in the tank absorbers because the water solar-heated the previous day is drawn into the automatic-heater storage tank when the evening baths are taken and does not reradiate during the night. Any type of auxiliary heater can be used—electric, gas, oil, or coal—that has automatic temperature controls.

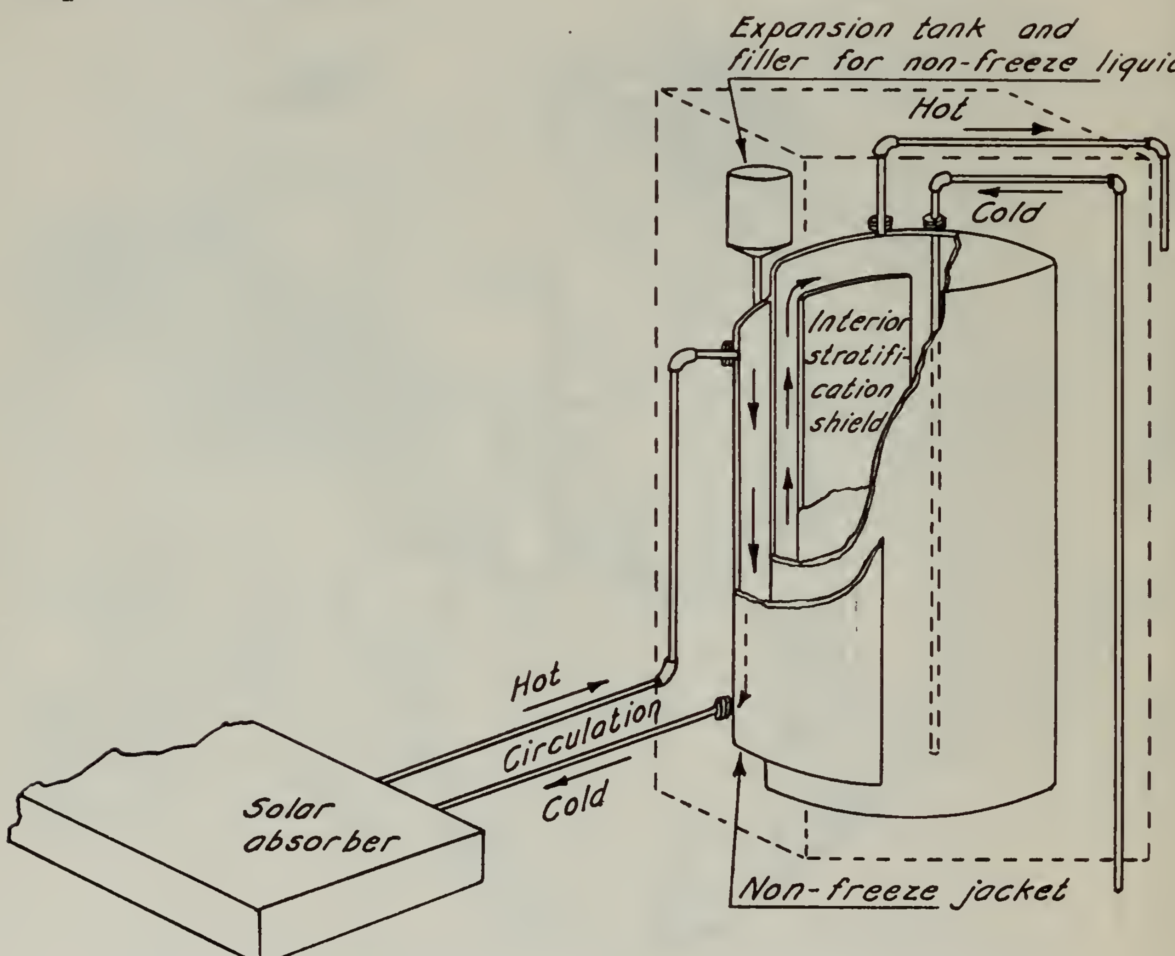

Fig. 23.—Commercial type nonfreezing solar-heater-system tank.

NONFREEZING SOLAR-ENERGY ABSORBERS

A solar heater used in combination with an automatic heater can be operated to advantage throughout the winter if the danger of pipe absorber freezing can be avoided. There is not much danger of freezing during ordinary nocturnal radiation frosts on calm, clear nights when the air temperature remains only a few degrees below 32° F for a short time (fig. 17) because of the high heat capacity of the pipe, water, and insulation. Freezing temperatures with wind, however, are almost sure to do damage unless there is considerable reverse circulation at night drawing warm tank water through the cold pipes. Such reverse circulation occurring with low-level storage tanks is ordinarily very objec-

tionable in wasting heat previously absorbed. Usually the ordinary pipe absorber must be drained during periods of freezing temperatures if damage is to be avoided. If frost warnings are not received regularly, it is good practice to drain the absorber as soon as the weather is cold enough for house heating.

TABLE 8

PHYSICAL PROPERTIES OF WATER, ALCOHOL SOLUTION, BRINE, AND LIGHT SPRAY OIL

Item	Fluid characteristics, with unit or base	Water	Alcohol, 15 per cent solution*	Sodium chloride,† 24 per cent solution	No. 1 tank-mix spray oil
1	Freezing point, °F	32	20	1	....
2	Pour point, °F	....	....	....	below 0
3	Specific gravity, at 68° F	0.9983	0.971	1.18	0.865
4	A.P.I. gravity, degrees A.P.I.	....	....	....	32
5	Density, pounds per cu. ft. at 95° F	62.056	60.3	73.2	53.2
6	Thermal volumetric expansion per °F at 95° F	0.000193	0.000176	0.000247	0.0004
7	Thermal density change, pounds per cu. ft. °F	−0.012	−0.011	−0.018	−0.022
8	Viscosity, pounds per ft. sec. at 95° F	0.00048	0.00079	0.00087	0.0036 to 0.0053
9	Saybolt viscosity, seconds at 100° F	....	....	....	45 to 55
10	Thermosiphon flow criterion, $\frac{\text{density change}}{\text{viscosity} \times 24.7}$	1.00	0.55	0.84	0.24 to 0.17
11	Specific heat at 95° F	0.997	0.947	0.80	0.46
12	Heat-flow criterion, $\frac{\text{items } 3 \times 10 \times 11}{0.997}$	1.00	0.50	0.79	0.08
13	$\sqrt[3]{\text{Heat-flow criterion}}$	1.00	0.87	0.95	0.60
14	Thermal conductivity $\frac{\text{B.t.u. per sq. ft.}}{\text{°F per ft.}}$	0.346	0.310	0.284	0.086
15	$\sqrt[5]{(\text{Thermal conductivity})^4}$	0.4278	0.3918	0.3653	0.1405
16	Solar-heater criterion(28) $\frac{\text{items } 13 \times 15}{0.4278}$	1.00	0.80	0.82	0.20
17	Boiling point, °F at 1 atmosphere	212	190	224	500(approx.)
18	Flash point, °F at 1 atmosphere	....	....	....	270
19	Fire point, °F at 1 atmosphere	....	....	....	290
20	Burning point, °F at 1 atmosphere	....	....	....	500

* By weight.

† Should be normalized for use in black iron pipe with about ¼ per cent sodium chromate ($Na_2Cr_2O_7$) plus enough lye (NaOH) to turn pink litmus paper blue.

The covered tank absorber (fig. 7) is practically nonfreezing in the valley and coastal areas because of the large heat content of the water and the large volume of the tanks, which are very difficult to freeze solid. The connecting pipes are, of course, susceptible to freezing and should be well insulated.

Commercial Nonfreeze Type Solar Water Heater.—The usual commercial type solar heater is of the type in which a nonfreezing solution is used in a separate circulating system (fig. 23). In one of these designs(12) the absorber fluid flows through the jacket space around the storage tank and does not mix with the usable hot water. This circulating fluid merely transfers heat from the pipe absorber to the storage

tank, and being separate from the usable water in the storage tank it can be any suitable nonfreezing solution. Standard tanks with internal coils but without stratification shields are obtainable from plumbing-supply houses. These can be connected (fig. 23) with an expansion chamber for the separate nonfreeze circulating fluid, but will not give high-temperature water quickly.

Separate Fluids for Nonfreezing Solar-Energy Absorbers.—Various ingredients can be added to water to lower its freezing point. The most common solutions are alcohol mixtures and brines. Other fluids not having the freezing characteristic of water might also be used, notably oil. Addition of alcohol to water is the simplest nonfreeze expedient; but as the alcohol vaporizes rather easily in a solar heater and the solution weakens, some addition should be made every fall. Various brine solutions, widely used industrially for refrigeration, are recommended for nonfreeze solutions where the operator is familiar with the operating technique to avoid corrosion in black iron pipe. The lightest grade of highly refined spray oil is the most suitable of the petroleum products, but does not circulate readily under thermal density differential head. Table 8 indicates the important characteristics of these three nonfreeze fluids and of water. As shown in item 16 light spray oil is only one-fifth as effective as water as a thermosiphon heat-transfer medium. This means that the absorber when filled with oil would operate at much higher temperature than when filled with water and would be less effective because of large absorber heat losses unless forced circulation is used.

CONSTRUCTION OF SOLAR ENERGY ABSORBERS

Essential features of solar absorbers are the absorber pipes or tanks, the insulated box, and the glass cover. The angle of slope toward the south is not very important except that for winter operation the slope should favor the winter sun, which at noon is only about 30° above the horizon in California. Most solar absorbers are placed on sloping roofs and it is much simpler to keep the same slope than to provide a special slope for the absorber. In case of new construction, seasonal solar heaters should be placed on roofs of ¼ to ⅓ pitch, and all-year absorbers on ⅓ or ½-pitch roofs.

The construction details for the insulated box should conform with regular structural practice, and many different designs will give excellent results if the simple requirements are met. Separate boxes mounted in the yard where there is no shade or on a pergola do not differ much in structure from the common roof box.

Construction Procedure for a Built-in Absorber Box on a New Roof.—When absorbers are built right into the roof structure the simplest procedure (fig. 24) is to (1) sheathe solid the underside of the rafters; (2) fill the rafter space with bulk insulating material such as redwood bark fiber, mineral wool, processed rice hulls, or the equivalent; (3) solid-sheathe on top of the rafters the same as for regular roofing; (4) frame in the sides of absorber box; (5) lay galvanized iron pan with edges turned up and bottom soldered and provided with screened drain

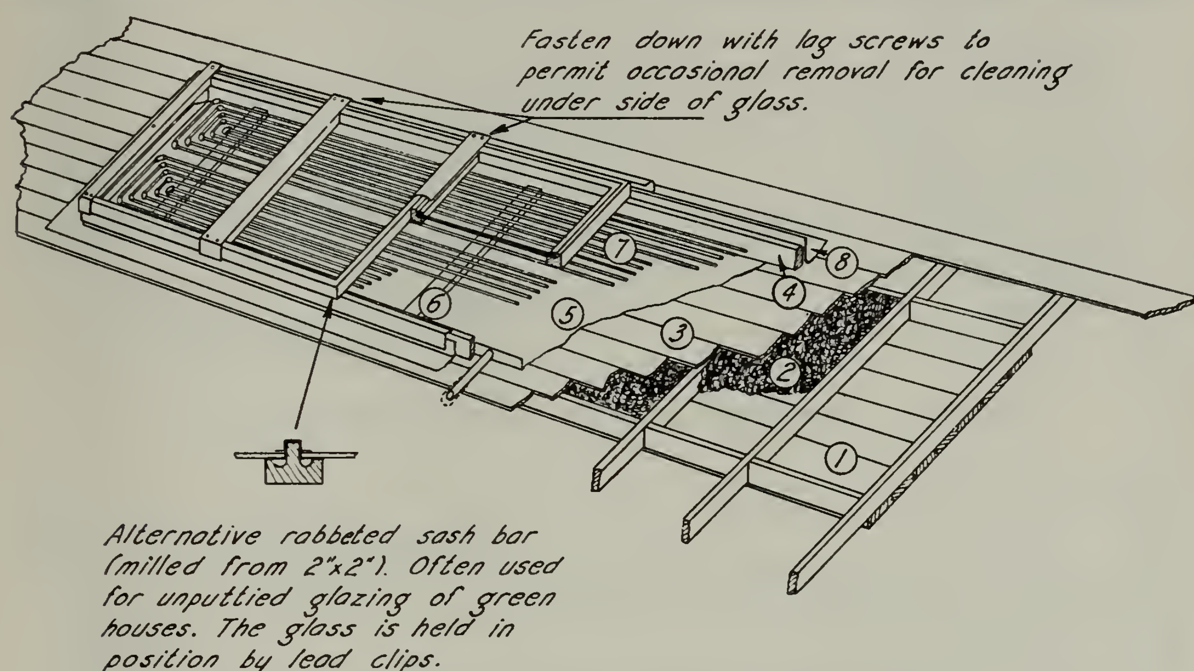

Fig. 24.—Construction plan of pipe-absorber roof box.

pipe to carry off possible leaks from pipe joints or broken glass; (6) nail on furring strips to support pipe coils or tanks; (7) install pipe coils, being sure of a continuous rise from bottom to top; (8) flash around the outside; (9) paint black all over; and (10) glaze in accordance with regular skylight practice.

Removable Glazed Cover.—The glazed frames must be removable for spring cleaning of the underside of the glass and for servicing the pipes or tanks in case of trouble. It is also desirable to place the solar heater in front of an attic window to facilitate cleaning of the outside surface, which in some localities should be done as often as once a month.

The shape of the absorber depends upon the glass sash used. Hotbed sash 3×6 feet is the cheapest but has considerable wood area; four sash would be needed for a 60-gallon system. If the absorber box can be long, single-light window sash 18×48 inches can be used, twelve being required for a 60-gallon system. In this case the puttying at the bottom must be brought up on the glass far enough to drain off the water when the window sash is in its sloped position. In all cases the pipe must rise

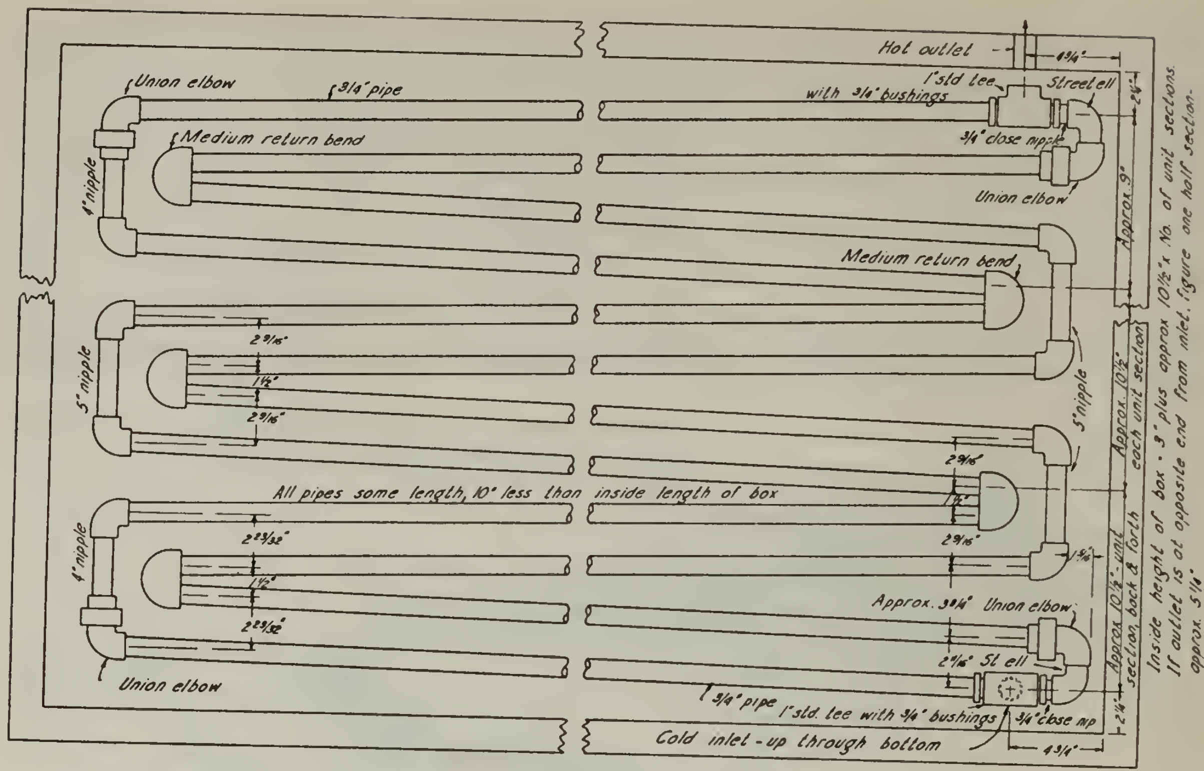

Fig. 25.—Absorber piping diagram for two pipes in parallel.

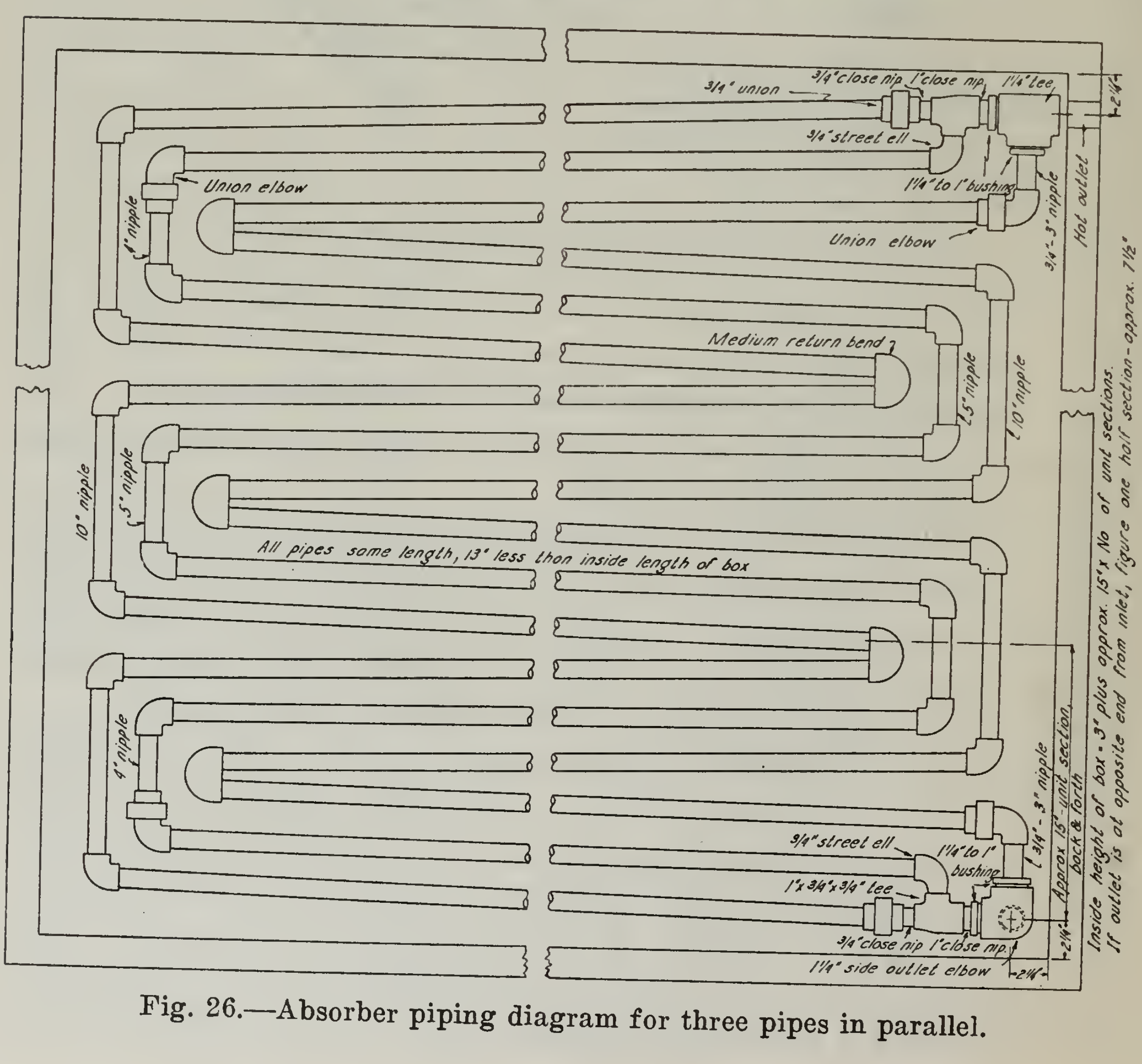

Fig. 26.—Absorber piping diagram for three pipes in parallel.

continuously from the drain to the storage tank. Any dip in the absorber coils will form an air pocket and seriously interfere with the thermosiphon circulation.

Parallel-Pipe Absorber Coils.—The common pipe absorber is a zigzag of ¾-inch pipe, and this is suitable for small solar heaters. If the total length of pipe in the single-coil type is so long in comparison with the effective riser height that thermosiphon flow is unduly restricted and provides only very small quantities of excessively hot water, the solar-

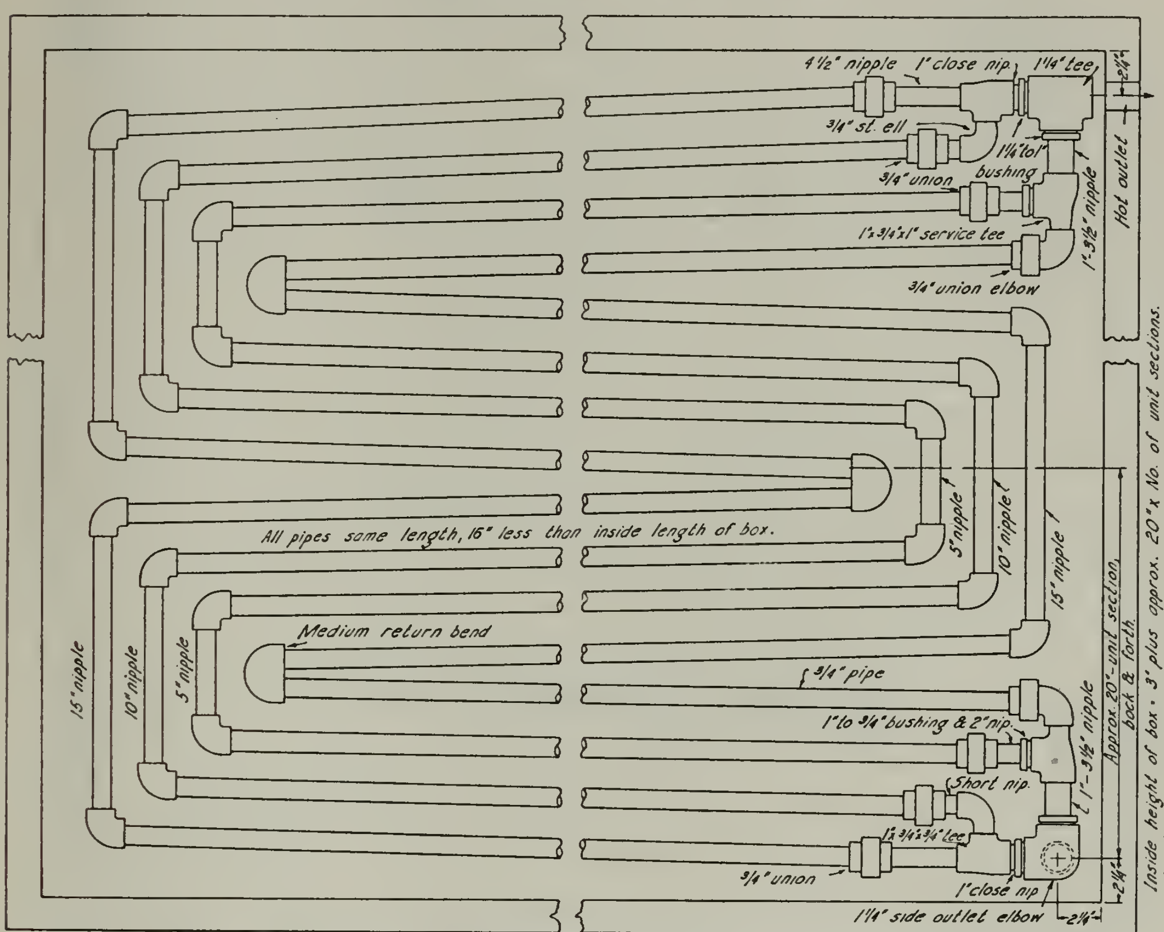

Fig. 27.—Absorber piping diagram for four pipes in parallel.

absorber heat losses are large because of operating at unnecessarily high temperature. One can then improve the efficiency by paralleling the absorber pipes to reduce the length of each line and also to divide the flow into multiple paths.

Figures 25, 26, and 27 show the fittings and pipe lengths for two-, three-, and four-parallel-pipe absorbers. The combination of fittings shown gives the closest pipe spacing possible and a practical covering of absorber area. The methods shown of making the terminal connections also permit the use of all equal-length pipe runs from end to end. In the two and three-pipe systems one union is located at the opposite end of the box, top and bottom, to preserve the equal-length feature of the

main pipe lengths. The diagrams, though not complete, give the unit-section dimensions so that the full installation can be easily sketched. Such pipe systems have, of course, considerable flexibility: the unit sections are easily stretched out or compressed a little, and ordinary inaccuracies in pipe lengths will give no trouble.

Figures 28 and 29 show the five- and six-parallel-pipe absorbers using the standard branch-tee connection for the terminals. Complicated sys-

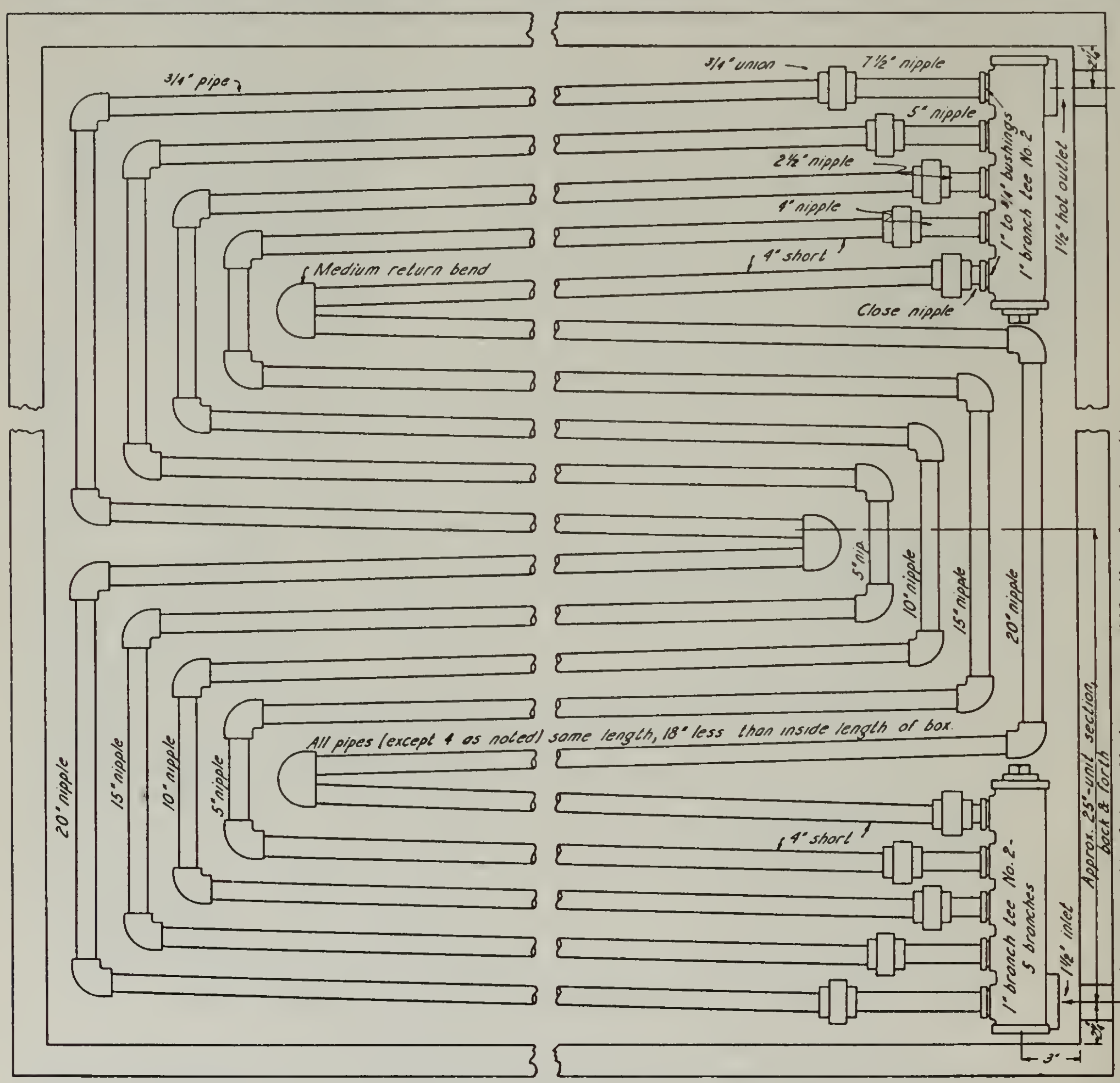

Fig. 28.—Absorber piping for five pipes in parallel using branch-tee terminals.

tems of separate pipe fittings might be used, but the 1½ inlet and outlet fitting is too large to maintain the close pipe spacing shown in figures 25, 26, and 27. Branch tees were commonly used for industrial wall pipe radiators, but because of the present preference for cast radiator sections these branch tees are not always carried in stock by plumbing-supply houses. They are, however, readily obtainable on order and give a much neater pipe absorber. With the branch tees the two pipes connecting at the ends must be shorter than all the rest to allow for the unions.

Methods of Obtaining Greater Heat Output from Limited Absorber Area.—Usually the most economical method of obtaining greater heat output is to increase the absorber area and extend the simple pipe coils. When, however, the available space for a solar absorber is limited, the equivalent of about 20 per cent greater absorber area can be obtained by embedding the ordinary pipe coil to half-pipe diameter in cement

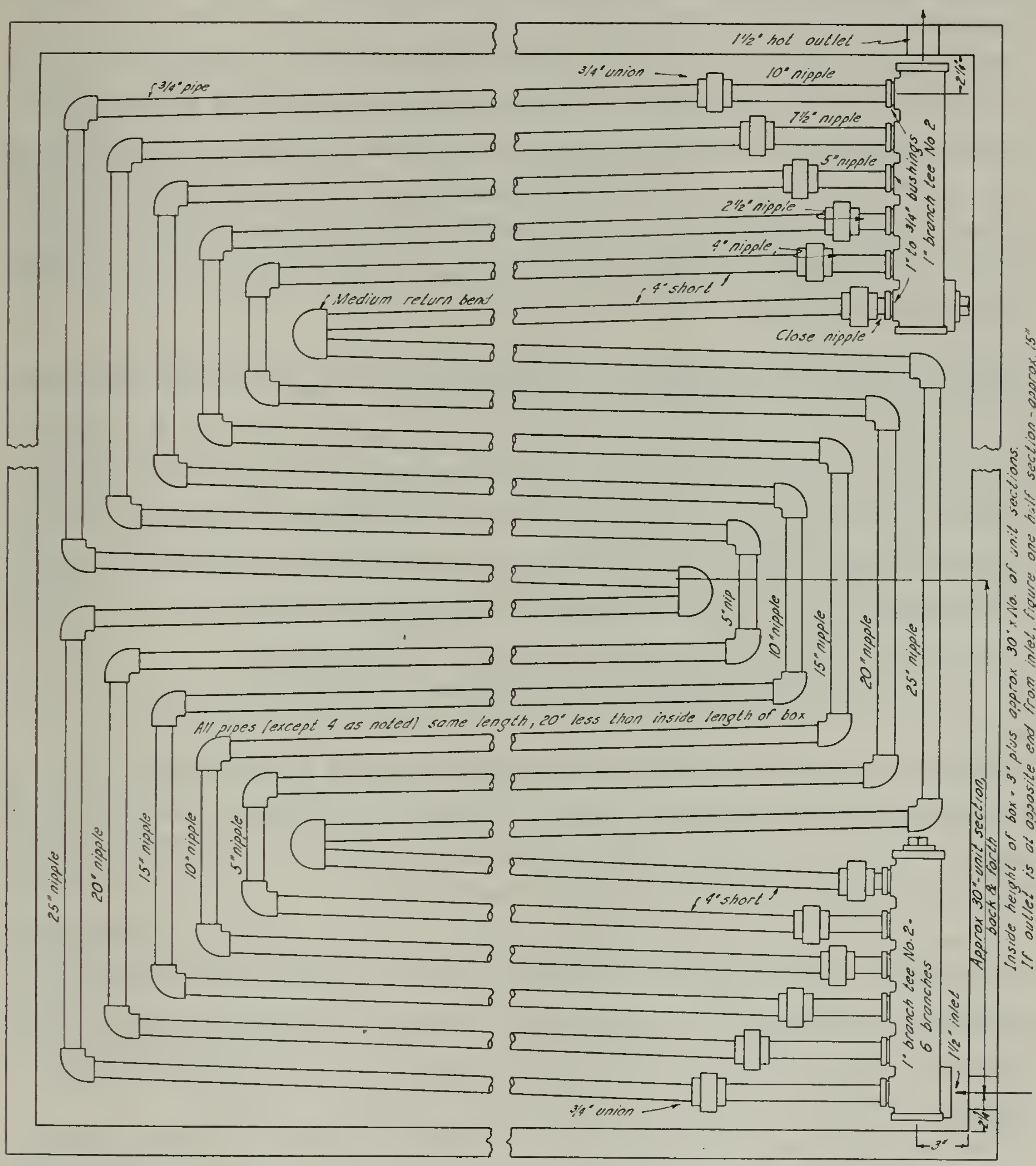

Fig. 29.—Absorber piping for six pipes in parallel using branch-tee terminals.

mortar. This arrangement provides a better means of transfer for the heat generated in the space between the pipes to the pipes themselves. A suitable concrete mixture is made of 1 part cement and 4 parts sand. After the cement has dried, the whole surface should be painted black.

Cast wall-radiator sections would be much superior to pipe absorbers because the reduced open space and the depth of the section will catch

almost all the direct sunshine. The objection to extra weight is not serious, and their use is recommended if enough sections for 80 per cent of the designed pipe-absorber area happen to be available at the same cost as pipe and fittings. A radiator section cracked by freezing would of course be more expensive to repair than a cracked branch tee, and both these are much more expensive and cause more delay than the repair of a burst pipe or fitting.

Thin flat tanks covering the entire absorber area need have only 70 per cent of the area specified for ordinary pipe coils. This type of equipment can be made to order and might prove advantageous for nonfreeze-type solar absorbers in which the circulating fluid is not subject to high water pressure. The proper thickness of metal and the number of stay-bolts required depend upon the size of the absorber units and the height of the overflow pipe.

INITIAL COST AND CARRYING CHARGES OF SOLAR WATER HEATERS

The sunshine is free, and every surface exposed to the sun is heated at no cost, but to obtain useful energy for heating water some apparatus is necessary and this usually requires an expenditure which connotes an interest charge. Then, too, the apparatus deteriorates because of rusting and exposure, so that some annual depreciation charge also should be considered. There are operation costs, even though very low, because of the care required for cleaning the glass and replacing occasional broken panes.

The heat output of a solar water heater cannot be specified exactly in comparison with auxiliary heaters because the auxiliary heater is operated only when needed, whereas the solar heater, operating whenever there is sunshine, is of value only when used.

In many places, such as isolated cabins or houses where the fire hazard of auxiliary water heaters is objectionable, the relative cost of solar heaters is not important. In other cases where full automatic water heaters are needed anyway, the carrying charges of a solar absorber must be compared with the bare cost of fuel or electricity it saves.

Cost of Commercial Solar Water Heaters.—The nonfreeze commercial solar water heater with special tank is sold at the factory for about $3 per gallon capacity. The installed prices, including insulation, extra pipe and fittings, labor, and the like are about $5 per gallon. The small systems have a slightly higher cost than these figures.

By assuming a useful life of eighteen years and servicing costs for renewal of alcohol and repairs at 4 cents per gallon capacity a year, the total annual cost will average about 47 cents per gallon capacity a year.

Each gallon capacity represents a free heat absorption of about 1,000 B.t.u. per day, and the nonfreeze type can be assumed to be fully operative for about 270 days a year. These assumptions indicate a solar heat cost per 1,000 B.t.u. of about $\frac{1}{6}$ cent, which is equivalent to an electricity rate of 6 mills per kw.-hr. when fully utilized.

Cost of Common Pipe-Coil Solar Water Heater.—A standard pipe-coil solar heater system (figs. 19 and 20) can be installed for about $3 per gallon capacity. By assuming for this type a useful life of about fifteen years and 210 days per year of full operation, the solar heat costs about $\frac{1}{9}$ cent per 1,000 B.t.u., which is about equal to the cost when using natural gas in the Sacramento Valley.

If the solar-heater system is installed by the owner and the cost considered is that for materials only, these annual carrying charges might be halved, in which case the solar heater would compete economically with the manual fuel-oil heater, which is bothersome and a fire hazard.

Cost of Solar Absorber Tank Heaters.—The 30-gallon range boilers, hotbed sash, and insulation can be obtained for about 60 cents per gallon for the enclosed tank heater shown in figure 7. If fully utilized, this installation furnishes hot water at a cost of about $\frac{1}{25}$ cent per gallon. The least expensive system, the exposed second-hand tank (fig. 6) for afternoon showers, heats water on sunshiny days for no appreciable cost.

SUMMARY OF USE AND CONSTRUCTION

Enclosed 30-gallon hot-water boilers with glass covers can be used as solar heaters without pipe-absorber coils and will furnish two or three hot showers per tank in the late afternoon or evening of bright sunshiny days. These tank absorbers do not keep their high temperatures overnight and are not a satisfactory means of obtaining hot water for washing clothes.

The glass area of the ordinary pipe-coil absorber should be about as large in square feet as the number of gallons of storage-tank capacity. The $\frac{3}{4}$-inch pipes are conveniently spaced about $2\frac{3}{4}$ or 3 inches center to center and usually should be arranged in parallel circuits to avoid excessive temperature rise. The length of single pipe of about 70 to 100 feet when the absorber discharges into the storage tank about 7 feet above the center of the absorber gives over 30° F temperature rise, which is adequate. When the tank inlet is lower, the single-pipe length should be reduced in proportion.

The insulated storage tank used with regular pipe-coil absorbers should have a capacity equal to the whole day's hot water demand because about half of the hot water is often used after sunset and about

half is often needed early in the morning before the sunshine has time to heat much water.

To insure a constant supply of hot water regardless of the weather, the hot outlet pipe from the solar-heater storage tank can be connected to the cold inlet of an automatic auxiliary heater. Then if the solar-heated water is not up to thermostat-control temperature the automatic heater will operate to raise the temperature to the desired point. When there is good sunshine the water entering the automatic heater whenever a faucet is opened will already be hot enough, and the auxiliary heater need not operate. With such a combination system the housewife will never be bothered by lukewarm water, yet will save heating expense when the sun shines.

LITERATURE CITED

[1] ANONYMOUS.
1934. Items. Science **80**(2078) Supplement p. 7.

[2] ANONYMOUS.
1935. Increased light values with white paint. Indus. and Engin. Chem., News ed. **13**(19):397.

[3] ABBOT, CHARLES G.
1922. The reflecting power of clouds. Smithsn. Inst. Astrophys. Observ. Astrophys. Ann. 4:375–381. (See specifically p. 379.)

[4] ABBOT, CHARLES G.
1929. The sun. 433 p. (See specifically pages 116, 298.) D. Appleton & Co., New York.

[5] ABBOT, CHARLES G.
1934. How the sun warms the earth. *In:* Smithsn. Inst. Ann. Rept. **1933**:1–476. (See specifically p. 157.)

[6] ABBOT, CHARLES G.
1936. Solar energy now caught with 15% efficiency. Science News Letter Jan. 11, 1936. p. 23.

[7] BUILDING RESEARCH BOARD.
1933. [Gt. Brit.] Dept. Sci. and Indus. Research, Bldg. Research Bd. Rept. **1932**:88, 90.

[8] CALLENDER, J. H.
1934. Aluminum foil for insulation. Architectural Forum **60**(1):68.

[9] COBLENTZ, W. W., and C. W. HUGHES.
1925. Emissive tests of paints for decreasing or increasing heat radiation from surfaces. U. S. Dept. Com., Bur. Standards Technol. Papers **18**(254):177.

[10] COBLENTZ, W. W., and H. KAHLER.
1921. A new spectropyrheliometer and measurements of the component radiations from the sun.... U. S. Dept. Com., Bur. Standards Sci. Papers **16**(378):240–41.

[11] COHN, WILLI M.
1934. New means of producing extremely high temperatures. Glass Indus. 15(7):149–50.

[12] DAY AND NIGHT WATER HEATER COMPANY.
1932. Day and night solar water heater. (Advertising circular.) Day and Night Water Heater Co., Ltd., Monrovia, California.

[13] DAY, PRESTON C.
1917. Relative humidities and vapor pressures over the United States. U. S. Mo. Weather Rev. Sup. 6:25, 59.

[14] ELVEY, C. T. [Yerkes Observatory.]
1934. Some observations of the sun through a dust storm. U. S. Mo. Weather Rev. 62(6):201–2.

[15] FISHENDON, M., and O. A. SAUNDERS.
1932. The calculation of heat transmission. 280 p. (See specifically p. 17–22.) His Majesty's Stationery Office, London.

[16] FOWLE, FREDERICK E.
1933. Smithsonian physical tables. 8th revised ed. 682 p. (See specifically p. 378, 381.) Smithsonian Institution, Washington, D. C.

[17] HAND, IRVING F.
1934. The character and magnitude of the dense dust-cloud which passed over Washington, D. C., May 11, 1934. U. S. Mo. Weather Rev. 62(5):156.

[18] HOTTLE, HOYT C.
1934. Radiant heat transmission. *In:* Chemical Engineers' Handbook. 2,609 p. (See specifically p. 883.) McGraw-Hill Book Co., New York.

[19] INTERNATIONAL CRITICAL TABLES.
1929. Table 5. Albedo; white light. *In:* International Critical Tables. vol. 5, 470 p. (See specifically p. 262.) McGraw-Hill Book Co., New York.

[20] JONES, H. SPENCER.
1934. Aluminum surfaced mirrors. Nature 133(3363):552. London.

[21] KALITIN, N. N.
1930. The measurements of the albedo of a snow cover. U. S. Mo. Weather Rev. 58:59–61.

[22] KIMBALL, H. H.
1924. Records of total solar radiation intensity and their relation to daylight intensity. U. S. Mo. Weather Rev. 52:474, 478. Figs. 1, 4.

[23] KIMBALL, H. H.
1926. [Review of] A. Angstrom: The albedo of various surfaces of ground. U. S. Mo. Weather Rev. 54:453.

[24] KIMBALL, H. H.
1928. The distribution of energy in the visible spectrum of sunlight, sky-light and total daylight. International Illuminating Congress [Saranac Inn, New York] Paper No. 12^{-4}:10.

[25] KIMBALL, H. H.
1929. [Review of] G. C. Simpson: Distribution of terrestrial radiation. U. S. Mo. Weather Rev. 57:340.

[26] KIMBALL, H. H.
1929. Solar observations. U. S. Mo. Weather Rev. 57:26–27.

[27] KING, W. J.
1932. The basic laws and data of heat transmission. Mech. Engin. [New York] 54(7):496.

[28] MCADAMS, WM. H.
1933. Heat transmission. 383 p. (See specifically p. 45–49 and p. 210, equation 43.) McGraw-Hill Book Co., New York.

[29] PERRY, JOHN H.
1934. Flow in pipes, ducts and channels. *In:* Chemical Engineers' Handbook. 2,609 p. (See specifically p. 736–740.) McGraw-Hill Book Co., New York.

[30] PRIEST, IRWIN G.
1935. The Priest-Lange reflectometer applied to nearly white porcelain enamels. U. S. Dept. Com., Bur. Standards Jour. Research 15:544.

[31] SCHACK, ALFRED.
1933. Industrial heat transfer. 371 p. (See specifically p. 354–6.) John Wiley & Sons, Inc., New York.

[32] SCHMIDT, E.
1927. Wärmestrahlung technischer Oberflächen bei gewöhnlicher Temperatur. Beihefte zum Gesundheits-Ingenieur. Reihe 1, Heft 20:1–21. R. Oldenbourg, München and Berlin.

[33] SCHMIDT, E.
1934. Thermal radiation of water and ice and of frosted and wet surfaces. Refrig. Engin. 28(3):152, 156.

[34] UNITED STATES DEPARTMENT OF AGRICULTURE, WEATHER BUREAU.
1925–34. Climatological data. U. S. Mo. Weather Rev. 53–62.

[35] UNITED STATES DEPARTMENT OF AGRICULTURE, WEATHER BUREAU.
1929–35. Solar observations. U. S. Weather Rev. 57–63.

[36] UNITED STATES DEPARTMENT OF AGRICULTURE, WEATHER BUREAU.
1933. [Maps of frost dates and growing season.] U. S. Dept. Agr. Climatological Data, California section 37:40, 48, 56, 64, 71.

[37] VAN DUSEN, M. S.
1934. Sheet steel as insulation. Refrig. Engin. 28(3):152.

15*m*-10,'36